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# THESIS

PRECISION OF TIDAL DATUMS IN THE
SACRAMENTO RIVER, CALIFORNIA

by

Timothy Alan Bouquet

June 1980

Thesis Advisor: W. C. Thompson

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to determine 19-year tidal characteristics as a function of river level, from which are determined the 19-year datums. The accuracy of tidal datums, indicated by the standard deviation, is found to be within 0.1 foot in the lower bay system and within 0.2 foot upriver.

Precision of Tidal Datums in the
Sacramento River, California


by


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Submitted in partial fulfillment of the
requirements for the degree of


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## ABSTRACT

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## ACKNOWLEDGEMENTS

# I.  INTRODUCTION

A tidal datum is a plane of reference for elevations
determined from measurements of the rise and fall of the
tides.  Water depths and tide heights are referenced to these
datums.  High-water datums are used in the United States
for the determination of property boundaries.  A low-water
datum is used for nautical charting so that actual depths
will normally be greater than those charted.  In areas of
gradually sloping shoreline, the shoreline position can vary
dramatically with the choice of reference datum.

In tidal rivers, such as the Sacramento River of California,
the distance the measurable tide reaches upriver varies in-
versely with the river stage.  At upriver stations the tides
vanish at high river levels.  On the navigable rivers
draining the Atlantic slope of the Appalachian Mountains,
the upriver limit of the ocean tides is a well-defined
physiographic boundary known regionally as the fall line.
On the Sacramento River, on the other hand, there is no
convenient natural upriver barrier to the tides.  The
National Ocean Survey (NOS) is the responsible agency of the
U.S. Government for tide prediction, nautical charting, and
tidal-datum determination in domestic waters.  They are
presented in the Sacramento River, and many other rivers as
well, with the problem of how far up the river system to

carry tide guaging for the purpose of tidal datum determination. This study investigates that problem.

The Sacramento River was chosen for study because of the availability of tide data collected over a common time period at a large number of tide stations in the river delta and the San Francisco Bay System by a cooperative California/ National Ocean Survey tide program conducted in 1977-1979. NOS is planning both a coastal mapping program and a complete hydrographic survey of the San Francisco Bay and its tributaries as a part of their intensive investigation in the San Francisco Bay System.

This study does not directly answer the question of how far gauging should be carried up the river system, that being a policy decision to be made by NOS, but presents information that might serve as a basis for making such a decision. Data on tidal characteristics and on the quality of tidal datums in the Sacramento River are presented to provide this basis. The results may serve as a guide to the solution of tidal datum surfaces in other tidal rivers as well. Primary questions addressed include: (1) How do tidal characteristics vary with superelevation of the river (the height of the river surface above sea level), (2) with what accuracy can tidal datums be determined in the river system from a short series of observations, and (3) what quantitative criteria might be used to decide whether the river should be judged

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tidal, or not, for the purpose of datum-plane determination? The focus of the analysis is primarily on question (2). This question is examined by computing equvalent 19-year tidal datums using a short series of tide observations at secondary tide stations in the river system, derived from comparison of simultaneous observations at an oceanic reference tide station having a long tidal history. The standard procedure for comparison of simultaneous observations used by NOS [Marmer, 1951] was used as a basis for datum analysis in the Sacramento River.

This study will in effect develop 19-year datums and ranges from a series of short observations for tide stations in the Sacramento River above Presidio, San Francisco to Sacramento, and then analyze the accuracy of these determined datums. This will be done using raw hourly heights by first separating the dominant harmonic tidal components from the non-harmonic river fluctuations. Then the heights and times of high and low waters at the secondary tide stations will be computed for comparison with the same tides at Presidio to determine the 19-year datums and ranges using the standard procedure. A least-squares technique will then be used to define relationships between river levels and computed tidal datums and ranges. The variability of the determined datums represents the accuracy of datum determination by the standard procedure for comparison of simultaneous observation in the Sacramento River System.

## II. LOWER SACRAMENTO RIVER SYSTEM

The Sacramento River System considered in this investigation extends approximately from the City of Sacramento, down the main channel of the Sacramento River to Suisun Bay, thence along the tidal channel that runs through Suisun and San Pablo Bays of the San Francisco Bay system to terminate at the Presidio tide guage in the entrance to the San Francisco Bay (Figure 1). Sacramento is located near the upper limit of tidal influence. Presidio, on the other hand, is considered here to be situated in an oceanic tidal environment where daily water-level variations are primarily tidal in nature. Between these two stations lies the tide-river transition zone which upriver is subject in diminishing degrees to the influence of the tides and in increasing degrees to the influence of the river. Between the City of Sacramento and Suisun Bay the river traverses the delta of the Sacramento, San Joaquin, and several smaller rivers. Water levels in the Sacramento River below the confluence of the San Joaquin River near Collinsville often reflect runoff from both major rivers, but above Collinsville the river level is determined mainly by runoff of the Sacramento.

Nine tide observation stations in the Sacramento River System were chosen for analysis in order to present a picture of the tidal and river characteristics throughout the

tide-river transition zone (Table 1). These stations were
selected for their even distribution along the river system,
and to represent each tidal regime along the river system.
The Sacramento River at Sacramento, at a distance of about
111 nautical miles (NM) upriver from San Francisco, is about
200 yards wide, and has a charted depth of about 10 feet (low
river stage). At Walnut Grove, downriver 28 NM and below
several meanders, the river is even narrower (about 100
yards wide) and about the same depth. At Three Mile Slough
the river widens to half a mile and is over 20 feet in depth.
Further down, the San Joaquin joins the Sacramento as it
empties into Suisun Bay. Collinsville is located at this
juncture. Mallard Island is 4 NM westward of this point and
exhibits similar tides to those at Collinsville. Suisun
Bay widens considerably (to 5 NM) and narrows again at
Benicia, which is at the eastern entrance to Carquinez
Strait. This strait is a constricted channel cut through
rolling hills that connects Suisun Bay with San Pablo Bay
to the west. Port Orient is located in the southern portion
of San Pablo Bay, just 10 NM north of San Francisco. The
long-term primary tide station used for comparisons in this
study is the gauge at Presidio, San Francisco.

This river system presents several interesting features
for tidal studies. These include the extensive lower bay
system in immediate and open communication with the Pacific

Ocean through the Golden Gate, the constriction of Carquinez
Strait, the upper bay system comprising mainly Suisun Bay,
and upstream from that the delta region where the tide wave
is divided among numerous tributaries and sloughs.

To relate the datums throughout the river system, all
measurements and datums were reduced to the National Geodetic
Vertical Datum (NGVD), which is the standard geodetic reference
datum for elevations in the United States. Tide-staff eleva-
tions relative to NGVD are given in Table 2. There is a
possibility of subsidence in the Sacramento River Delta. The
most recent geodetic leveling in the delta was carried out in
1964 and 1965. No attempt was made in this study to deter-
mine or account for subsidence.

Annual variations of river level at Sacramento are so
great as to eliminate any tidal influence during periods
of high water. Figures 2A and 2B show twenty years of mean
monthly water levels at Sacramento, 1958-1978 [Zeile, 1979].
Winter water levels above 20 feet can be seen in some of the
prominent winter peaks. Summer lows are usually, but not
always, below five feet NGVD. Note in Figure 2B the "drought
years" of 1976 and 1977 when the winter water levels were
lower than the average summer lows. Table 3 which includes
statistics for Sacramento is a primary product of this study.
Mean river levels at Sacramento for the 18-month period of
this study were statistically typical for the river over many

years, as can be seen from a comparison with the monthly
mean river level for the 19-year period 1960-1978 (Table 3).
Extreme variability of the river during the study period was
not as great as is sometimes found during the previous 19
years.

## III. TIDAL DATUMS AND RANGES

Two high waters and two low waters each day characterize
the semi-diurnal mixed tides which are found on the Pacific
coast of the United States. The two high and two low tides
are normally of different heights, thereby providing a higher
high water (HHW), a lower high water (LHW), a higher low
water (HLW) and a lower low water (LLW) each day. The sequence
of these four water levels varies throughout the fortnightly
tide cycle. Every 14 days the tides go through a cycle of
both reduced range (neap tides) and increased range (spring
tides) due to changes in phase of the primary lunar and solar
harmonic tidal constituents. Arithmetic means of these water
levels over any chosen observation period produce four primary
tidal datums, MHHW, MLHW, MHLW, and MLLW. From these are
derived the following tidal datums which are the datums used
in navigation and in property boundary determinations:
(1) mean high water, MHW, which is one half of the sum of
the MHHW and the MLHW, (2) mean low water, MLW, which is
similarly the mean of the MHLW and the MLLW, and (3) mean
tide level, MTL, the mean of the MHW and MLW [Marmer, 1951].
These datums are listed in Table 4.

Mean sea level, MSL, is derived from the mean of hourly
heights rather than from water level extremum values. In
this study it was computed only for Presidio for inclusion

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in Table 5. The terminology mean river level, MRL, is used interchangeably with mean tide level, MTL, for stations upriver where the tidal influence is greatly reduced, their mathematical derivations being the same.

Tidal ranges are a measure of the mean amplitude of the tide and are derived from differences in elevation of the tidal datums. The mean range, MN, is the difference between the MHW and the MLW. The height difference between the MHHW and the MHW is the diurnal high inequality, DHQ. Similarly, the difference between the MLW and the MLLW is the diurnal low inequality, DLQ. The diurnal or greater range, GR, is the height difference between the MHHW and the MLLW.

By computing tidal datums from observations over a 19-year period, termed a tidal epoch, virtually all significant astronomical cycles can be averaged out, thereby providing datums which, in the absence of eustatic sea level or land elevation changes, are stable. The period of the longest tidal constituent of significance, caused by regression of the moon's nodes, is 18.6 years, but 19 years is used in practice to average out the larger amplitude yearly tide cycle. Because of long-term variations in sea level, it is necessary to specify the 19-year epoch used for computing datums. The 1960-1978 epoch, which NOS intends to adopt as a replacement for the 1941-1959 epoch [Hicks, 1980], is used as the reference for the datums and ranges presented in this study.

The elevations of the tidal datums and ranges for the epoch 1960-1978 at Presidio, San Francisco, which were used as the standard for comparison with the secondary stations in the Sacramento River system are given in Table 5. Included in Table 5 are the elevations of the previous epoch of 1941-1959 used in other studies, and the datums for the 18-month period of this study.

## IV. DATA AND EDITING

The tide observations analyzed in this study were
acquired on magnetic tape, tide gauge analog record, and
paper computer printout from NOS and the U.S. Geological
Survey (USGS). These are listed in Table 2. Digital tide
data for Presidio for January and February 1978 were unavail-
able, so heights of high and low waters were read directly
off the analog bubbler gauge record supplied by NOS; for these
two months the times of the predicted tides were considered
adequate since they do not affect datum determination by
the comparison of simultaneous observations procedure. Hourly
heights were extracted from both the 15-minute computer print-
out supplied by USGS and the six-minute magnetic tapes
supplied by NOS for systematic computer handling. These
hourly heights were used to compute, by a procedure described
later, the times and heights of high and low waters, which in
turn were used to compute 19-year datums and ranges by the
method of comparison of simultaneous observations. Tide data
for Hercules was not analyzed due to the limited amount of
data available.

Due to equipment malfunctions, gaps occurred in all of
the tide records (Table 2). Short gaps in the record of up
to three days were interpolated to within 0.1 foot by using
the pattern of the previous and subsequent tides as a guide.

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Here, ten days of hourly heights were plotted on the same
48-hour graph as five lines centered around the gap. The
missing tides were then interpolated by hand to best fit the
pattern. Gaps longer than three days could not be inter-
polated with acceptable certainty. Mallard Island, Collinsville,
Three Mile Slough, and Walnut Grove contained uneditable gaps,
requiring special handling in computations. All datum and
range computations were performed for the whole study period
of 1/1/78 - 6/30/79 except for the uneditable gaps.

# V.   PROCEDURES AND ANALYSIS

Programs described here extract the tidal component
from the edited hourly heights, determine the heights and
times of high and low waters, sort these tides by daily
type, and then determine tidal datums by the comparison of
simultaneous observations procedure.  This procedure compares
the same tides at a short-term or secondary station with a
long-term reference or standard station.  Graphical presenta-
tions and analysis of these extended 19-year datums for the
1960-1978 epoch were then produced.  The important programs
are included in the Appendix.  All computations were performed
on the IBM 360 digital computer at the W. R. Church Computer
Center of the Naval Postgraduate School.  Graphics were pro-
duced on the Versatec plotter attached to the computer.

## A.   HIGH AND LOW WATERS PROGRAM

For the purpose of computing datums by the procedure
of comparison of simultaneous observations, the times and
heights of high and low waters are required.  To obtain these
values from the digital hourly height data, a second-degree
polynomial was fitted using a least-squares procedure to the
hourly heights.  This parabola-fitting procedure, which is
fully described by Zeile [1979], consists of two steps.
First, four successive hourly heights are scanned in a moving

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window for a trend or slope. Whenever these heights show a change in the sign of the differences in successive hourly heights, this is used as an initial guess for an extreme water. Upon detection of a change in trend, the five hourly heights distributed around the sign change are then fitted with a polynomial. The point on the curve with a zero derivative is then used as the time and height of the extreme water. This procedure provides heights accurate within a tenth of a foot. For a more refined determination of the tide time and height upriver where the tide wave is clearly assymetrical, a third or fourth order polynomial might be more appropriate for some purposes. This refinement is not justified here in view of the fact that variations in river height greatly exceed the accuracy with which tide heights can be determined.

## B. TIDE SELECTION AT PRESIDIO

In order to determine tidal datums the tides must be sorted by daily tide type. Since all river stations were compared with the Presidio reference station, all tides at Presidio were indexed by daily tide type. It is normally a simple task to distinguish the higher high, lower high, higher low, and lower low waters by their relative heights. When two consecutive high or low waters have the same height, it is adequate to follow the previous day's pattern.

Since the average period between consecutive tides is a little longer than six hours, every fortnight there occurs a

solar day containing only three tides. For accurate datum
determination it is essential that the tide type of the three
tides be determined. The Manual of Tide Observations [USCGS,
1965, p. 54] recommends for hand comparison that the previous
day's tide pattern be used for a guide to the pattern for the
three-tide day. This procedure usually works well, but is
inadequate on those occasions when a change in tide type
sequence occurs simultaneously with a three-tide day.
Attempts to use the previous day as a guide sometimes failed
early in this study because the day-to-day change in tide
height is occasionally greater than the diurnal high or low
inequality. A satisfactory solution, developed by the author,
is to use the relative heights of the four waters occurring
before noon on the day of the three-tide day as a guide for
the tide or tides in the A.M. and the subsequent four waters
as a guide for the water or waters occurring in the P.M.
This identifies tide types in a consistent manner.

## C. HARMONIC FILTERING PROGRAMS

During high river levels at upriver stations the range
of the tide may be reduced to approximately the level of
noise, which has a magnitude of about a tenth of a foot
[Zeile, 1979]. The river height at which tides can be
identified at a given station can be increased by separating
the prominent semi-diurnal and diurnal tidal components from
the non-harmonic river components of the water level. This

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was done by computing running means of the hourly heights using averaging intervals determined by the periods of the harmonic components to be suppressed, i.e., 24 hours for the solar component and 25 hours for the principal lunar component ($2M_2 = 24.96$ hours). Application of these filters applied singly and in combination is illustrated in Figure 3 for a 24-day series of tide measurements at Presidio. The upper two curves, displaced vertically for ease of comparison, show the residual water level remaining after application of the 25-hour filter (upper curve) and the 24-hour filter (lower curve). The middle set of curves shows the effect of double filtering with both 24 and 25-hour running mean filters and the triple filter recommended by Godin [1966], compared with the 24-hour filter. It may be seen in this example that the double filter eliminates these harmonic components almost as effectively as the triple filter. Use of the triple filter, which requires a little more computing time, yields only an incremental improvement over the double filter; accordingly, a double filter was used in this study. The residual, which at river stations represents the river component of the observed water level history, can then be subtracted from the hourly heights to extract the tidal component to be used in the comparison of simultaneous observations. This procedure was used for the uppermost river stations, Walnut Grove and Sacramento, because they both

experienced high enough water levels so that the tide would get lost among the noise.

An additional filter was used to eliminate fictitious tides (non-tidal water-level fluctuations mistaken for tides) occurring at Sacramento during periods of high river level. Zeile [1979] found that an actual tide wave would not arrive at Sacramento sooner than 6.5 or later than 14.5 hours after it passed Presidio. Accordingly, the time of tide at Sacramento was compared to that at Presidio, and if the lag was less than 6.5 hours it was considered fictitious and ignored. If the lag was greater than 14.5 hours it was assumed there was a missed tide; accordingly, the tide was nevertheless used as an estimate of the missing tide and also for the next comparison. This crude method produces an acceptable approximation of the mean river level, but other datums and ranges derived at river levels above tidal influence have no significance.

For the lower river stations, where fictitious and missing tides did not occur, the time lag from when the wave passed Presidio to the time it arrived at the secondary station was used to synchronize the array of high and low waters at the river station with the corresponding waters at the standard station. Travel times used were from the Tide Tables [NOS, 1978].

## D. COMPARISON OF SIMULTANEOUS OBSERVATIONS PROGRAM

Tide observations at all river stations were compared to those at Presidio, San Francisco using the standard comparison of simultaneous observations procedure which is explained in detail by Marmer (1951). Two assumptions are made in the use of this procedure: (1) The difference between the mean tide level over the period of observation and the actual 19-year mean tide level is the same at both the standard and subordinate stations, and (2) the ratios of the observed ranges to the actual 19-year ranges are the same for both stations.

This procedure, which may best be understood from examination of the program given in the Appendix, first separates the tides by type (HHW, LHW, HLW, and LLW) at both stations. The mean of each tide type at the secondary station is then computed for the comparison period. Differences in height between the same tide at the reference and secondary stations are averaged over the comparison interval yielding mean differences for each tide type. The time differences in the occurrence of common tides at the two stations are used to compute the high water and low water time lags between the two stations. The elevations of the datum planes and the ranges as described in Table 4 are then computed for the period of the common tide observations for both stations. Range ratios are computed using the differences in the common

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datum elevations between the stations and the ranges at the
secondary station. These are then multiplied by the 19-year
epoch ranges for the Presidio reference station (given in
Table 5) to derive effective 19-year ranges (1960-1978 epoch)
for the subordinate station.

The mean tide level over the observation period for the
secondary station is adjusted to an effective 19-year mean
tide level by applying the difference between the observed
mean tide level and the established 19-year mean tide level
at Presidio to the observed mean tide level at the secondary
station. Effective 19-year high and low water datums are then
computed from the effective 19-year mean tide level and the
19-year ranges.

E. STATISTICAL ANALYSIS AND GRAPHICS PLOTTING

Numerous customized computer programs were written to
produce the many statistical data analyses and graphics
presented in this report. None are included in the Appendix.
The principal products include the following:

1. Time Series Graphs

Continuous 19-year datums and ranges were generated
and plotted for each river station by the comparison of
simultaneous observations procedure using a running 28-day
observation period and a one-day computation step. Examples
of these time series graphs, which show the seasonal

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variability of these datums and ranges, appear in Figures 11
and 12 for Sacramento. Similar Graphs for all the river
stations are included in Appendix A.

2. Datums and Ranges along the River System

To show the extreme values found in the data during
the study period, a maximum, or peak, and a minimum were
computed for each data set, and are included in Tables 11-19.
Differences between these extreme values are listed in Table 9.
Mean values were computed for each data set over the 18-month
study period and these are included in Table 6, and plotted
for the length of the river in Figure 5. High water and low
water values from the 18-month study period are provided for
each 19-year datum and range at each station (Tables 7 and 8).
These statistics are also plotted for the length of the river
system from Presidio to Sacramento (Figures 7-10).

3. Scatter Plots and Regression Lines

The 19-year datums and ranges were also plotted
against the 28-day mean tide level for each station and are
in Appendix A. For an example of one of these scatter plots,
see Figure 15. A least-squares procedure was used to fit a
straight line of regression to each data set, providing a
mathematical relationship between the 28-day river level at
each station and the computed 19-year datums and ranges. The stan-
dard deviation of each data set about the line of regression was
also computed to provide a measure of the variability of each

relationship. The slope and y-intercept of the lines of
regression were tabulated and are included in Tables 11-15
and 18. Graphs of these statistics along the river system
for each datum and range are included in Figures 16-24.

4. Datums and Ranges at Presidio

In order to illustrate the effects and variability
produced on datums and ranges by the use of various observa-
tion periods, tidal datums and ranges for Presidio for the
study period were computed and plotted using simple running
means of the various sample lengths (Figures 13-14, 26-31).
Mean datums and ranges computed for the entire study period
at Presidio are shown in Table 5.

5. Comparison of Observation Intervals

To demonstrate the accuracy of datum determination
with various short lengths of comparison, 19-year datums and
ranges were computed using 7, 14, 28, and 56-day observation
periods at Sacramento. Time series graphs of these are
found in Figures 11-12 and 32-37. Scatter graphs of these
datums and ranges against mean river level for each observa-
tion period at Sacramento are found in Appendix A; an example
is shown in Figure 38. Regression statistics for the scatter
graph data are found in Tables 16-19, and are plotted against
the length of comparison in Figures 39-47.

# VI. DISCUSSION

## A. TIDAL BEHAVIOR IN THE RIVER SYSTEM

Many of the characteristic features of tidal behavior
in the river system are illustrated in Figure 4, which
shows a short series of tide waves as they move upriver
from San Francisco Bay during a period of high river stage.
Simultaneous hourly heights for a two-day period are plotted
for eight stations from Presidio to Walnut Grove. The curve
for Sacramento is omitted, the mean river level being over
21 feet on these days and there being effectively no tides.
The figure shows that as tide waves travel upriver, their
range generally decreases and they arrive at each consecu-
tive station at a later time. Less obvious in this example
is asymmetry of the tide wave which develops upriver, the
high tide traveling faster than the low. One can also see
the increase in mean tide level upriver, the gradient of
which is determined by the prevailing river stage. It may be
noted that the MTL gradient increases markedly upriver from
Three Mile Slough where the Sacramento River is confined to
a narrow leveed channel. The increase in MTL can also be
seen in Figure 5, which shows the elevation relative to NGVD
of the derived 19-year datums throughout the river system
(discussed more fully below). Note in this figure that MLLW

lies below MTL at the Presidio as far as 70 NM upriver from the Presidio.

Another interesting phenomenon is the increase in tide range found at some of the lower river stations relative to the range found at Presidio. According to the Admiralty Tidal Handbook [1975], as a tide wave moves into a typical estuary, the range is amplified due to its confinement in a narrowing channel. This increase exhibited in the Sacramento River System can be seen in the increased mean tide range shown in Figure 6 at Point Orient. Note also a second increase in range found at Three Mile Slough (56 NM from Presidio). This apparent increase is due to the lack of low water (summer) data for the lower two stations, Collinsville and Mallard Island. Above Point Orient, Figures 5 and 6 both nicely show the decrease in range which is generally observed as the tide wave opposes the river current and gains in elevation. Tidal influence is found at elevations more than double the MHHW level at Presidio, demonstrating that the tidal energy indeed climbs uphill. The DLQ is reduced substantially, whereas the DHQ is only slightly affected upriver by the increase in elevation. The data for Figure 5 and 6 are found in Table 6.

Figures 7 and 8 (and Table 7) show the 19-year tidal datums and tidal ranges, derived from 28-day comparisons, that correspond to a time of lowest river level during the

study period when the tide reaches the farthest upriver. At these times the computed 19-year datum elevations are lowest and tide ranges are largest. Figure 7 shows a slight upriver decrease in elevation of MTL between Point Orient and Benicia and also between Three Mile Slough and Walnut Grove. Subsidence may be a factor at Three Mile Slough; however, a comparison of MTL in Figures 5, 7, and 9 suggests that subsidence said to be occurring in the Sacramento-San Joaquin Delta has been small. This elevation discrepancy may be entirely due to the lack of data for Three Mile Slough during the low water summer months.

Figures 9 and 10 (and Table 8) show the computed 19-year tidal datums and tidal ranges along the Sacramento River System, derived from 28-day comparisons, that roughly correspond to the highest water stage in the river system during the study period. The decrease in tidal ranges upriver is relatively rapid and there is essentially no tidal influence at Sacramento. The diurnal high and low water inequalities are seen to disappear upriver so that the tides tend to become semi-diurnal in type. Note in Figure 9 the flat MTL in San Pablo Bay and in Suisun Bay, and the gradient found between Point Orient and Benicia. The latter is considered to be due to the constriction of the Carquinez Strait.

B.  19-YEAR DATUMS AND RANGES IN THE RIVER SYSTEM

The standard NOS procedure for comparison of simultaneous observations is used to carry datums from a standard or primary tide station at which long-term 19-year datums have been established, to a secondary or subordinate short-term station.  This procedure is more accurate for longer periods of comparison than for short.  The commonly used length of comparison is one month.  This provides estimated 19-year datums having a standard deviation of 0.13 feet for oceanic tidal stations on the Pacific Coast within the same tide regime [Swanson, 1974].  Operational limitations have at times restricted tide observations to comparison intervals as short as a week or less, providing reduced accuracy. Because of the effect of length of comparison on accuracy of determination, a standard comparison period of 28 days was chosen for examining the effects of river superelevation on computed 19-year datums and ranges.  A 28-day period was selected because it minimizes the prominent fortnightly cycle of spring/neap tides, it is the length of a lunar month, it approximates the commonly used comparison period of one month, and also is short enough for convenient computation.

In order to examine the effect of length of the comparison period on computed 19-year datums and ranges, computations were also made using a series of intervals of 7, 14, 28, and 56 days  duration.  This series provides a geometric

progression from a short to a longer comparison interval,
including the 14-day interval which approximates the period
of the prominent spring/neap cycle. Longer lengths of
comparison did not provide a significant increase in accuracy
over that given by the 56-day interval.

The results of these comparisons are discussed in
Section B4.

1. Seasonal Datum and Range Variation

Upriver, the character of the tides varies considerably
throughout the seasons. Figure 11 shows running 19-year datums
at Sacramento derived from 28-day comparisons with the tides at
Presidio using a one-day computational time step. Figure 12
shows the corresponding ranges. Range values shown for the
periods of higher water level, above 10 feet NGVD, are essen-
tially computational noise created by comparison of river
flow fluctuations at Sacramento with real tides at Presidio.
The values for the MTL do present an accurate picture of the
mean water levels in the river. The largest 28-day greater
range, which occurs at lowest river levels, is about a foot
and a half.

Figures 13 and 14, which are presented here for com-
parison with Sacramento, show the variations in the datums
and ranges, respectively, found at Presidio for the same period.
These were produced by computing a simple running mean average
of the appropriate high and low waters. The pips and

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oscillations are computational artifacts resulting from the three-tide day, and occur with fortnightly frequency. Figure 13 shows fluctuations in the mean tide level which are primarily due to meteorological effects. The long-period harmonic fluctuations in tidal range, best shown in Figure 14, are attributed primarily to the annual and semi-annual harmonic components of the astronomical tidal forces. Similar graphs of datums and ranges were produced for 28-day comparisons for all the river stations and are included in Appendix A.

2. Influence of River Flow on 19-Year Datums and Ranges

Each 19-year datum and range was plotted against the 28-day mean tide level used to compute that datum and range for all of the river stations except Collinsville, and these graphs are included in Appendix A. Collinsville shows characteristics very similar to those at Mallard Island due to their proximity, and therefore has been excluded. With regard to terminology, mean river level is used interchangeably with mean tide level in places where the river flow is the major influence, even though both are computed from the mean of the high and low waters. These graphs are illuminating presentations of the range of 19-year values which would be expected from a comparison of simultaneous observations at each station knowing only the 28-day observed MTL. They also provide information on the variability of these datums and ranges with changes in river flow. The

circular patterns of data points exhibited in many of these graphs may be due to hydraulic differences between rising and falling river stages or to variations in contribution from the San Joaquin River.

In order to quantify the relationship between the 19-year datum or range and the observed 28-day MTL, a least-squares fit line of regression was computed for each data pair. The values for these are listed in Tables 11-15 and 18. The slopes given in the tables quantify the influence of the river flow on the datum or range shown. A zero slope indicates no river influence, a slope of one indicates no tidal influence, and a negative slope indicates an inverse relationship to river level. The significance of the y-intercept can be illustrated by imagining a cessation of river flow into the system. The mean water level of the entire system will then fall to sea level, and tidal ranges and datums will be primarily influenced by the geometry of the lower river system. Assuming the relationships computed from this data can be extrapolated to this low water case, the y-intercepts provide estimates of extreme values for the datum or range at unusually low water levels.

At Walnut Grove, for example, there is a definite decrease in the range of the tide as the MTL increases; this can be seen for the period of study in Figure 15. The linear relationship GR = 3.848 - 0.396 MTL can be fitted to this

data with a standard deviation of a tenth of a foot (see
also Table 15). The GR intercept indicates that the largest
28-day diurnal range that could be expected at Walnut Grove
is about 3.8 feet. The MTL intercept (or x-axis intercept)
provides an estimate of the water level at which there will
be no tide. This calculates to 9.7 feet NGVD. The equation
also gives the level at which the tide range equals the tenth
of a foot noise level as 9.5 feet NGVD. These values are
close to the river level at which the tide disappears also
at Sacramento.

Figures 16 through 24 show how these regression
variables for the period of study vary along the river system
for the five datums and four ranges of interest computed
using 28-day observations. These graphs show the relative
influence of the river flow and river system geometry on the
datums and ranges along the river system. The reliability
of these relationships is indicated by the standard deviation,
plotted as squares. The degree of river level influence
on the datums is indicated by the slope, plotted as triangles,
with a zero slope indicating no river influence and a slope
of one indicating no tidal influence. The influence of the
geometry of the river system on the datums and ranges can be
seen in the y-intercept values, plotted as circles, which are
estimates for the 19-year datums or ranges which would be
expected from a cessation of river flow.

Figures 16-20 show the variability of the 19-year MTL, MLLW, MLW, MHW, and MHHW datums from Presidio to Sacramento. The general increase of the slope upriver for all five datums clearly shows an upriver increase in the influence of river stage on the datums. Even in the lower bay system, the MTL and high water datums are influenced by river flow as is shown by the small positive slopes at Point Orient.

The standard deviation for all datums is lowest in the lower bay system (less than 0.1 foot), and generally increases upriver. It is 0.15 foot or less for all datums except for the low water datums at Sacramento, the latter being 0.18 foot. These small standard deviations indicate a very close relationship between datum elevations and the river level, and provide the basis for specifying a set of 19-year datum planes throughout the river system that are independent of the river level.

Nineteen-year high and low water datums are computed from the sum of a range and the 19-year mean tide level. Accordingly, the standard deviation of a high or low water datum will be equal to the root mean square of the standard deviation of the 19-year range and 19-year MTL. Any error in the computation of the 19-year MTL will contribute significantly to errors in computation of the high and low water datums; therefore, any improvement in the 19-year MTL determination in a river system will significantly improve the datum determinations.

Statistics on the 19-year ranges are shown in Figures 21 and 22. The slopes calculated for the greater range and mean range show similar patterns, increasing with increasing mean tide level (positive slope) till about halfway up the river system, where the superelevation causes a decrease in range (negative slope). There is a point about 60 NM upriver where the slope is zero, indicating that the ranges are independent of the river level. At Sacramento the slope again approaches zero due to the numerous water level data above the influence of the tides. A more negative slope value would be found at Sacramento if the regression was computed only for the low river levels which are subject to tidal influence. It is interesting to note that in the lower portions of the river system a tidal range amplification results with increases in mean tide level.

The effects of river flow on the inequalities are shown in Figures 23 and 24. The DHQ is little affected by the changes in river level, the slope of the statistical distribution being approximately zero regardless of river level throughout the river system. The variability of the 19-year DHQ averages less than 0.1 foot throughout the river system, and is about 0.02 foot everywhere below the narrow channel sector of the river. The DLQ, on the other hand, is noticeably affected by the superelevation, disappearing in the upper river even at stages of low river flow.

3.  Relation between Sacramento and Other River Stations

Figure 25 shows the 28-day mean tide levels for all
the river stations plotted against the mean river levels for
the same 28-day interval at Sacramento.  This figure can be
used to estimate the 28-day observed MTL expected for any
station downriver knowing the 28-day mean river level at
Sacramento.  Lines of regression were fitted to these rela-
tionships and the statistics from these are shown in Table 20.
Reference can then be made to the individual station graphs
in Appendix A to determine probable values for datums and
ranges at that river level.  Using standard tide tables of
predicted tides for San Francisco, the linear relationships
shown in Figure 25, and the real time mean river level at
Sacramento, water levels and tide ranges can be then pre-
dicted for the stations in between.

4.  Accuracy of Datum Determination from Short Observations

At secondary stations, a short series of tide observa-
tions is compared to a reference station for computation of
19-year datums.  A one-year observation interval is a
standard recording period used by NOS for secondary stations
today.  Mean datums and ranges were produced for Sacramento
over the 18-month period of this study and are included in
Table 3.  Data limitations restricted the ability in this
study to produce statistics on the reliability of a one-year
length of comparison in the river system.  It was also

considered that results obtained using one-year data samples could be accurately extrapolated from the products derived using shorter sample intervals and that they would not differ much from the 28 and 56-day results. The latter proved to be the case. Hydrographic survey limitations occasionally require comparisons to be made from shorter periods of observation, NOS Form 248 being used for comparisons of seven-day or fewer observations.

In this study it was decided to use a series of short-period observations for the purpose of evaluating the effects of the length of tide observations on the effective 19-year datums and ranges produced. Accordingly, four observation intervals were chosen of 7, 14, 28, and 56 days. Seven days approximates the shortest series of tide observations generally used historically in hydrographic surveying, as stated above, and 28 days approximates the commonly used one-month comparison interval. It may be noted that the interval of 14 days is the closest full-day approximation to the prominent fortnightly cycle of spring/neap tides, and so any averaging over this period or its multiples would be expected to minimize variations in the means obtained. The four observation intervals were also selected to form a geometric progression to simplify interpolation or extrapolation of results obtained to other tide observation periods than these.

In order to present a picture of how the water levels can vary over short observation periods and of the effects of averaging these variations, 7, 14, 28, and 56-day running means of the tide heights and their differences at Presidio were computed for the study period. Time series plots of these are shown in Figures 13 and 14 and 26-31. The variability of the prominent fortnightly tide cycle can be clearly seen in Figures 26-29 produced from the 7 and 14-day running means. Figures 30 and 31, produced from a 56-day running mean, effectively average out these fortnightly variations.

For contrast, the effects of 7, 14, 28, and 56-day tide observations at a river station are shown in Figures 11 and 12 and 32-37 for Sacramento. These figures show the fluctuations of the river to greatly exceed the tidal influence; nevertheless, the fortnightly spring/neap cycles appear prominently in the ranges computed from a seven-day comparison in Figure 33 during low river stages. Figure 36 shows the damping effect of a longer comparison interval on both the river and spring/neap fluctuations, and Figure 37 shows the corresponding ranges.

Evaluations of the effect of the length of tide observations over the study period on computed 19-year datums and ranges were performed using tide data from Sacramento. Scatter graphs, such as shown in Figure 38 of the 19-year datums and ranges plotted against the computed

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mean river level for the same comparison interval, were prepared for each of the four comparison intervals and are included in Appendix A. A line of regression, which may be thought of as a line of datums or ranges, was computed for each of these scatter graphs and the statistics developed are given in Tables 16-19 and are graphically summarized in Figures 39-47. The figures and tables give the slope and y-axis intercept of the lines of regression and the standard deviation of the data points about this line, each plotted against the length of comparison.

The figures show that the slope values and y-intercept are very nearly independent of the tide observation period. The standard deviations, however, show a definite decrease with increased length of comparison for all 19-year datums and ranges. An eightfold increase in the length of comparison, from 7 to 56 days, reduces the standard deviation of the 19-year MTL about the short-term observed mean river level by a factor of two according to Figure 39. A similar reduction in the standard deviation about the lines of regression for the other datums and ranges can be seen in Figures 40-47. The scatter graphs show that most of the variability of these standard deviations occurs at lower river levels, the tides disappearing at high water levels.

Swanson [1974] used the standard procedure for comparison of simultaneous observations to compute the accuracy

of datum determination with comparison intervals ranging
from one month to one year for oceanic stations in the same
tide regime. His graphs also show dependency of the the
accuracy on the length of comparison. The standard deviations
shown in Figure 42 for MHW and in Figure 43 for MHHW are very
nearly identical to the standard deviations for these high
waters found by Swanson [1974, p. 11-12, Figures 8 and 10]
over the common sampling interval (one to two months) for the
standard method of comparison on the Pacific coast. The
rate of accuracy change with sampling interval for the over-
lapping data are in agreement; therefore, the rate of change
determined by Swanson can be used to estimate the accuracy
which would be expected at Sacramento from even longer
comparison intervals than presented here. Swanson's data
all pertain to oceanic tide stations where river effects
on the water level are negligible. Thus, it is of particular
interest here to note that the dependency of the accuracy of
high water datum determination on the length of observation
is independent of whether the secondary station is located
in the oceanic or riverine environment.

Accuracy of computed 19-year low water datums show a
similar rate of improvement with longer sampling intervals,
but the accuracy of low water datum determination in this
river system is about 40% lower than it is for high water
datums. These determinations for low water datums show

standard deviations of up to 0.180 foot at Sacramento, which
is 35% less accurate than the low water standard deviations
found by Swanson for the West Coast.  Surprisingly, it is
about the same as the 0.183 foot standard deviation he found
for the Gulf Coast using the standard procedure.  The
accuracy of determination of the mean tide level found here
is close to that found by Swanson [1974, p. 12, Figure 10].

# VII. CONCLUSIONS

The standard method of comparison of simultaneous observations can be applied in the Sacramento River system in order to produce internally consistent 19-year datums and ranges. The validity of using this procedure is based on the fact that linear relationships can be developed between the datums and ranges and the river levels. Considering the variability of river fluctuations, the reduction in precision of determination that occurs upriver appears acceptable. Two assumptions are made in the use of the procedure: (1) The difference between the mean tide level over the period of observation and the actual 19-year mean tide level is the same at both the standard and subordinate stations, and (2) the ratio of the observed ranges to the actual 19-year ranges is the same for both stations.

In regard to the first assumption, for a secondary station located where river discharge produces a water-level superelevation above the ocean level, a weakness of the standard comparison procedure applied in a river system is the method of determination of the 19-year MTL. The standard procedure applies the height difference between the observed MTL at the primary station and its 19-year MTL, termed a corrector, to the observed MTL at the secondary station. This difference may amount to a foot at Presidio for a

seven-day observation period and half a foot for a 28-day period. This difference cannot be expected to travel up-river as a constant quantity but should undergo a reduction and/or amplification proportional to that experienced by the ranges or inequalities. A question remains as how to best apply this difference upriver. It is possible that the difference diminishes rapidly upriver as does the diurnal low inequality. This can be determined with assurance only from a long series of observations at secondary stations. It should be pointed out that applying this corrector in a place where it is inappropriate induces oscillations in the 19-year MTL which are not real. A comparison of the MTL in Figure 26 with the MTL in Figure 32 shows that the fluctuations are the inverse of one another, indicating that this MTL corrector is inappropriately applied at Sacramento.

The second assumption appears valid for all probable mean river levels at all secondary stations, except Benicia, there being a well-defined linear correlation between river level and range reduction or amplification through the river system (Tables 11-15 and 18, Figures 21 and 22). An unusual situation occurs at Benicia where it was difficult to get a close linear fit between the ranges and the mean river level (Figures 21 and 22). The diurnal low inequality at low river levels was found often to behave as if the lowest waters could not overcome the seaward current through Carquinez Strait.

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Tidal ranges diminish with increased superelevation of the water level in the Sacramento River, disappearing completely at certain high river stages except in San Pablo Bay where some range amplification is seen with the relatively small superelevation which occurs there. The diurnal low inequality is affected more by the river superelevation than is the diurnal high inequality.

The 19-year mean tide levels and high water tidal datums can be computed in the river system with an accuracy comparable to that resulting from comparisons in an oceanic environment found by Swanson [1974] for the same observation interval. Low water datum determination is less accurate than high water determination in the river system. Nineteen-year tidal datums determined from short comparisons are dependent, though, on the specific superelevation of the river.

A method has been developed here having a straightforward statistical basis, using tide observations collected over observation periods on the order of a year at secondary river stations, where a 19-year record is available for both an oceanic reference station (Presidio) and a river reference station (Sacramento), for obtaining the elevation of the standard tidal datums along the full extent of the river system in which tidal oscillations occur.

The method involves determination of precise values for 19-year datums and ranges anywhere up the river system in the following way for a chosen mean river level. For each datum and range at each river station, precise regression equations have been developed expressing the computed 19-year datums and ranges as a function of the river level; these are given in Tables 11-19. Substituting the chosen river level into these equations, one can then calculate consistent datums and ranges by simply multiplying the MTL by the slope and then adding the y-intercept. For example, the monthly mean river level at Sacramento for the epoch years 1960-1978 is 7.54 feet NGVD (Table 3). From the relationships presented in Table 18, 19-year datums and ranges can then be computed around this mean river level for Sacramento for the epoch 1960-1978 and are included in Table 3. It may be noted from the table that the standard deviation of the mean river level over this 19-year period of observations is almost five feet.

In the example just considered, the mean of 19 years of river level measurements was chosen for establishing tidal datums for the 1960-1978 epoch for Sacramento. However, there are other logical choices of mean river level that can be derived from these long-term measurements around which tidal datums may be desired. These long-term river level measurements may provide a statistical basis for the choosing of suitable river levels around which to determine tidal datums. A histogram for this purpose is included as Figure 48 which shows the

height distribution of monthly mean river levels at Sacramento
for the eopch years 1960-1978.

For levee design or the determination of property boundaries,
a statistically high river level may be chosen. For navigation
purposes a low level datum would be chosen. With regard to the
latter, it may be noted in Table 3 (upper part) that the tidal
datums at Sacramento cluster about the long-term mean river
level, but that because of the wide variations in river ele-
vation, water levels below MLLW occur much of the time (lower
part). Accordingly, a datum for navigation at Sacramento
would best be chosen at a river level substantially below this
MLLW. In oceanic tide regimes, where tides are the only
influence on water level, fluctuations below the low water
datum chosen for navigation are statistically infrequent
and of small magnitude. In a river environment, a statisti-
cal low water level must be developed for both influences,
river level and tidal fluctuations. The data in Figure 48
might be used to choose a suitable low river level. Some
possible choices for a low water navigation reference at
Sacramento are: (1) the ten-percent quantile water level
(3.58 feet), which approximates the lowest waters in a normal
summer season at Sacramento, (2) the minimum value found in a
19-year record (1.98 feet, for 1960-1978), which is a low
water level in an unusuahly dry summer, and possibly (3) the
hypothetical river level if the river stopped flowing

altogether, which would be calculated by the MTL y-intercepts
as discussed previously (0.18 feet, Table 10). At any one
of these river levels, a MLLW with respect to that level can
be determined, and used as the nautical charting datum.
With any one of these choices it would be possible to
establish a datum which is continuous throughout the transition
zone of the Sacramento River System. In practice, tidal
zoning, defining separate datums for each section of the
river, would be required.

With regard to the question raised in the introduction,
results obtained here for the Sacramento River System show
that there is no natural discontinuity or feature along the
river system that can be objectively used to terminate up-
river tide measurements for datum determination purposes.
However, there are several possible criteria that might be
adopted for this purpose, each requiring an arbitrary speci-
fication: (1) A specified ratio of mean river superelevation
(MTL in Table 6) to the mean tide range (MN in Table 6),
(2) a specified ratio of river variability (manifested by
the MTL in Table 9) to tidal variability (GR in Table 6),
(3) a specified percentage of time that a tidal influence
prevails (for example, the point where the tide shows some
influence half of the time is where the median river super-
elevation equals the level of no tide; this point is above
nine feet upriver from Sacramento.

feet this point is upriver from Sacramento), and (4) the point above which the river has no tides. The position of the last choice cannot be determined from the data studied, but requires knowledge of the river gradient above Sacramento. Assuming the river gradient is similar above Sacramento to that below, the tides will travel an additional 100 NM beyond Sacramento at a low river level, based on the rate of range decrease along the confined section of the channel from Walnut Grove to Sacramento indicated in Figure 7 (Table 7).

The results of this study raise the following questions: (1) Can the procedure developed for the Sacramento River System be applied over the entire Sacramento-San Joaquin delta region, (2) over what extent of the Sacramento-San Joaquin delta region can the Sacramento 19-year reference station be used to determine water levels at other stations, and (3) is a separate reference station needed on the upper San Joaquin river system? The California/NOS cooperative tides program of 1977-1979 involved the synoptic collection of tide data from some 53 stations throughout the delta region above Carquinez Strait, and the California Division of Water Resources maintains some 43 longer term recording stations in the region. This wealth of data may provide the means for answering these questions.

Table 1. TIDE STATION LOCATIONS

| SYMBOL | STATION NAME | HYDROMORPHIC LOCATION | NAUTICAL MILES |
|--------|-------------|----------------------|----------------|
| P | PRESIDIO | GOLDEN GATE | 0 |
| O | POINT ORIENT | SAN PABLO BAY | 10 |
| H | HERCULES | SAN PABLO BAY | 17 |
| B | BENICIA | CARQUINEZ STRAIT | 31 |
| M | MALLARD ISLAND | EASTERN SUISUN BAY | 44 |
| C | COLLINSVILLE | *EASTERN SUISUN BAY | 48 |
| T | THREE MILE SLOUGH | WIDE RIVER CHANNEL | 56 |
| W | WALNUT GROVE | CONFINED RIVER CHANNEL | 83 |
| S | SACRAMENTO | CONFINED RIVER CHANNEL | 111 |

*River juncture, Sacramento-San Joaquin

Table 2. TIDE DATA

| STATION NAME | SOURCE & STATION NUMBER | DATA FORMAT | LEVEL OF NGVD ON STAFF[2] | OBSERVATION PERIOD | NUMBER OF GAPS EDITABLE | NUMBER OF GAPS UNEDITABLE |
|---|---|---|---|---|---|---|
| PRESIDIO | NOS | Analog Record | 8.61 | 1/1/78-2/30/78 | 2 | 0 |
| PRESIDIO | NOS 4290 | Mag. Tape[1] | 8.61 | 3/1/78-8/1/79 | 8 | 0 |
| POINT ORIENT | NOS 4881 | Mag. Tape | 9.92 | 1/2/78-5/7/79 | 2 | 0 |
| BENICIA | NOS 5111 | Mag. Tape | 30.70 | 2/2/78-7/1/79 | 2 | 0 |
| MALLARD ISLAND | NOS 5112 | Mag. Tape | 11.74 | 3/2/78-10/22/78 | 2 | 1 |
| COLLINSVILLE | NOS 5176 | Mag. Tape | 8.12 | 1/6/78-10/1/78 | 1 | 1 |
| THREE MILE SLOUGH | NOS 5236 | Mag. Tape | 8.15 | 1/9/78-6/30/79 | 2 | 5 |
| WALNUT GROVE | NOS 5489 | Mag. Tape | 6.72 | 1/1/78-6/30/79 | 1 | 3 |
| SACRAMENTO | USGS 11-4475 | Tabulation 15-Minute | 0.0 | 1/1/78-7/1/79 | 2 | 1 |

[1]Magnetic tape records are six-minute data from digital punch-tape gauges.

[2]Provided by NOS and USGS (written correspondence); the value for Walnut Grove is preliminary.

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## Table 3. TIDE DATA FOR SACRAMENTO

### All elevations and ranges are in feet.

| 19-YEAR DATUM | MEAN VALUES* FOR EPOCH 1960-1978 | MEAN VALUES FOR STUDY PERIOD 1/78-6/79 |
|---|---|---|
| MHHW | 7.99 NGVD | 7.40 NGVD |
| MHW | 7.77 | 7.17 |
| MRL | 7.54 | 6.85 |
| MLW | 7.17 | 6.53 |
| MLLW | 7.07 | 6.42 |
| **19-YEAR RANGE** | | |
| GR | 0.920 | 0.947 |
| MN | 0.602 | 0.642 |
| DHQ | 0.216 | 0.224 |
| DLQ | 0.100 | 0.108 |
| **STATISTICS FROM MONTHLY MEAN WATER LEVELS** | FOR EPOCH 1960-1978 | STUDY PERIOD 1/78-6/79 |
| MEAN | 7.54 NGVD | 7.07 NGVD |
| MEDIAN | 5.69 | 5.27 |
| MAXIMUM | 22.55 | 17.59 |
| MINIMUM | 1.98 | 3.67 |
| 10% QUANTILE | 3.58 | 3.75 |
| STD. DEVIATION | 4.73 | 4.20 |

*Computed from the mean river level of 7.54 (from
 lower part of table) and the relationships found
 in Table 18.

Table 4.   TIDAL DATUMS AND RANGES

Daily Tides:    HHW - Higher High Water

                LHW - Lower High Water

                HLW - Higher Low Water

                LLW - Lower Low Water


Tidal Datums:  MHHW - Mean Higher High Water

                MHW - Mean High Water = 1/2 (MHHW + MLHW)

               MLHW - Mean Lower High Water

                MTL - Mean Tide Level = 1/2 (MHW + MLW)

               MHLW - Mean Higher Low Water

                MLW - Mean Low Water  = 1/2 (MHLW + MLLW)

               MLLW - Mean Lower Low Water


Tidal Ranges:   DHQ - Diurnal High Inequality = MHHW - MHW

                DLQ - Diurnal Low Inequality  = MLW - MLLW

                 MN - Mean Range               = MHW - MLW

                 GR - Diurnal or Greater Range= MN + DHQ + DLQ

                                           or = MHHW - MLLW

## Table 5.  TIDE DATA FOR PRESIDIO

### All elevations and ranges are in feet.

| DATUM | EPOCH 1941-1959 STAFF | EPOCH 1941-1959 NGVD | EPOCH 1960-1978 STAFF | EPOCH 1960-1978 NGVD | STUDY PERIOD 1/78 - 7/79 NGVD |
|-------|-------|------|-------|------|------|
| MHHW | 11.46 | 2.85 | 11.60 | 2.99 | 3.00 |
| MHW | 10.86 | 2.25 | 11.00 | 2.39 | 2.44 |
| MTL | 8.86 | 0.25 | 8.95 | 0.34 | 0.42 |
| MSL | 8.80 | 0.19 | 8.90 | 0.29 | 0.31 |
| NGVD* | 8.61 | 0.00 | 8.61 | 0.00 | 0.00 |
| MLW | 6.87 | -1.74 | 6.90 | -1.71 | -1.61 |
| MLLW | 5.75 | -2.86 | 5.77 | -2.84 | -2.56 |

*Geodetic datum

| RANGE | EPOCH 1941-1959 | EPOCH 1960-1978 | STUDY PERIOD |
|-------|------|------|------|
| MN | 3.99 | 4.10 | 4.05 |
| GR | 5.71 | 5.83 | 5.56 |
| DHQ | 0.60 | 0.60 | 0.56 |
| DLQ | 1.12 | 1.13 | 0.95 |

TABLE 4: MEAN TIDAL DATUMS AND RANGES IN THE SACRAMENTO RIVER

derived from 28-day observation intervals

| 15-YEAR DATUM | STATION | | | | | | |
|---|---|---|---|---|---|---|---|
| | P | C | B | M | T | W | S |
| MHHW | 2.550 | 3.245 | 3.144 | 3.152 | 3.446 | 3.368 | 7.396 |
| MHW | 2.390 | 2.659 | 2.645 | 2.677 | 2.992 | 3.481 | 7.172 |
| MTL | 0.340 | 0.465 | 0.674 | 1.073 | 1.348 | 2.441 | 6.651 |
| MLW | -1.710 | -1.727 | -1.298 | -0.531 | -0.297 | 1.401 | 6.530 |
| MLLW | -2.840 | -3.247 | -2.532 | -1.455 | -1.181 | 0.988 | 6.422 |
| **15-YEAR RANGE** | | | | | | | |
| GR | 5.830 | 6.492 | 5.677 | 4.606 | 4.626 | 2.680 | 0.974 |
| MR | 4.100 | 4.385 | 3.543 | 3.207 | 3.289 | 2.080 | 0.642 |
| DHQ | 0.600 | 0.587 | 0.495 | 0.475 | 0.453 | 0.387 | 0.224 |
| DLQ | 1.130 | 1.520 | 1.234 | 0.924 | 0.884 | 0.413 | 0.108 |

TABLE 7: LOW WATER TIDAL DATUMS AND RANGES IN THE SACRAMENTO RIVER
derived from 28-day observation intervals

STATION

| 19-YEAR DATUM | P | C | P | M | T | W | S |
|---|---|---|---|---|---|---|---|
| MHHW | 2.550 | 3.040 | 2.840 | 2.910 | 3.010 | 3.110 | 4.140 |
| MHW | 2.390 | 2.450 | 2.350 | 2.420 | 2.560 | 2.730 | 3.650 |
| MTL | 0.240 | 0.310 | 0.460 | 0.870 | 0.540 | 1.640 | 3.350 |
| MLW | -1.710 | -1.920 | -1.500 | -0.690 | -0.690 | 0.540 | 2.840 |
| MLLW | -2.840 | -3.490 | -2.870 | -1.640 | -1.490 | 0.090 | 2.660 |

| 19-YEAR RANGE | P | C | P | M | T | W | S |
|---|---|---|---|---|---|---|---|
| GR | 5.830 | 6.900 | 6.110 | 4.900 | 4.550 | 3.240 | 1.550 |
| MR | 4.100 | 4.660 | 4.260 | 3.400 | 3.540 | 2.370 | 1.030 |
| DHQ | 0.660 | 0.620 | 0.560 | 0.520 | 0.500 | 0.470 | 0.480 |
| DLQ | 1.150 | 1.660 | 1.420 | 1.060 | 1.030 | 0.530 | 0.360 |

TABLE 8: HIGH WATER TIDAL DATUMS AND RANGES IN THE SACRAMENTO RIVER
derived from 28-day observation intervals

STATION

| 19-YEAR DATUM | P | O | B | M | I | W | S |
|---|---|---|---|---|---|---|---|
| MHHW | 2.550 | 3.520 | 3.440 | 3.390 | 3.780 | 6.270 | 17.270 |
| MHW | 2.390 | 2.930 | 2.550 | 2.940 | 3.340 | 6.260 | 17.270 |
| MTL | 0.340 | 0.430 | 0.510 | 1.320 | 1.700 | 5.610 | 17.170 |
| MLW | -1.710 | -1.610 | -1.100 | -0.280 | 0.110 | 4.950 | 17.140 |
| MLLW | -2.840 | -3.140 | -2.280 | -1.080 | -0.780 | 4.890 | 17.000 |

| 19-YEAR RANGE | P | O | B | M | I | W | S |
|---|---|---|---|---|---|---|---|
| GR | 5.830 | 6.360 | 5.280 | 4.300 | 4.410 | 1.380 | 0.150 |
| MN | 4.100 | 4.290 | 3.720 | 3.070 | 3.170 | 1.310 | 0.0 |
| DHQ | 0.600 | 0.540 | 0.430 | 0.400 | 0.380 | 0.0 | 0.0 |
| DLQ | 1.130 | 1.460 | 1.660 | 0.740 | 0.760 | 0.060 | 0.0 |

TABLE 9: DIFFERENCES BETWEEN MAXIMUM AND MINIMUM DATUMS AND RANGES
derived from 28-day observation intervals

STATION

| 19-YEAR DATUM | P | C | B | M | I | W | S |
|---|---|---|---|---|---|---|---|
| MHHW | 0.0 | 0.480 | 0.600 | 0.480 | 0.770 | 3.160 | 13.130 |
| MHW | 0.0 | 0.480 | 0.600 | 0.520 | 0.780 | 3.530 | 13.420 |
| MTL | 0.0 | 0.520 | 0.450 | 0.450 | 0.760 | 3.970 | 13.820 |
| MLW | 0.0 | 0.310 | 0.400 | 0.410 | 0.800 | 4.410 | 14.300 |
| MLLW | 0.0 | 0.350 | 0.550 | 0.560 | 0.710 | 4.800 | 14.400 |
| 19-YEAR RANGE | | | | | | | |
| GR | 0.0 | 0.540 | 0.830 | 0.600 | 0.540 | 1.860 | 1.400 |
| MN | 0.0 | 0.370 | 0.540 | 0.350 | 0.370 | 1.060 | 1.030 |
| DHQ | 0.0 | 0.080 | 0.130 | 0.120 | 0.120 | 0.470 | 0.480 |
| DLQ | 0.0 | 0.200 | 0.360 | 0.320 | 0.270 | 0.470 | 0.260 |

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TABLE 19: TIDAL DATUMS AND RANGES WITHOUT RIVER SUPERELEVATION (y-intercepts)
derived from 28-day observation intervals

STATION

| 15-YEAR DATUM | P | C | E | M | T | W | S |
|---|---|---|---|---|---|---|---|
| MHHW | 2.990 | 3.094 | 2.895 | 2.761 | 2.742 | 2.095 | 1.037 |
| MHW | 2.350 | 2.498 | 2.357 | 2.221 | 2.259 | 1.559 | 0.700 |
| MTL | 0.340 | 0.366 | 0.496 | 0.718 | 0.589 | 0.131 | 0.176 |
| MLW | -1.710 | -1.768 | -1.365 | -0.783 | -1.034 | -1.148 | -0.348 |
| MLLW | -2.840 | -2.226 | -2.440 | -1.568 | -1.787 | -1.751 | -0.516 |

| 15-YEAR RANGE | P | C | E | M | T | W | S |
|---|---|---|---|---|---|---|---|
| GR | 5.830 | 4.520 | 5.339 | 4.335 | 4.527 | 3.848 | 1.553 |
| MN | 4.100 | 4.265 | 3.722 | 3.005 | 3.292 | 2.707 | 1.047 |
| DHQ | 0.600 | 0.597 | 0.543 | 0.546 | 0.484 | 0.540 | 0.337 |
| DLQ | 1.130 | 1.459 | 1.075 | 0.785 | 0.752 | 0.602 | 0.168 |

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TABLE 11: STATISTICS FOR FLINT ERIENT

derived from 28-day observation intervals

| 19-YEAR DATUM | MEAN | MAXIMUM | MINIMUM | REGRESSION PARAMETERS | | |
|---|---|---|---|---|---|---|
| | | | | SLOPE | Y-INTERCEPT | STD DEVIATION |
| MHHW | 3.245 | 3.520 | 3.040 | 0.266 | 3.094 | 0.077 |
| MHW | 2.656 | 2.930 | 2.450 | 0.282 | 2.498 | 0.076 |
| MTL | 0.465 | 0.630 | 0.310 | 0.176 | 0.366 | 0.052 |
| MLW | -1.127 | -1.610 | -1.920 | 0.072 | -1.768 | 0.051 |
| MLLW | -3.247 | -3.140 | -3.490 | -0.036 | -3.226 | 0.069 |
| 19-YEAR RANGE | | | | | | |
| GR | 6.452 | 6.900 | 6.360 | 0.303 | 6.320 | 0.103 |
| MN | 4.365 | 4.660 | 4.290 | 0.411 | 4.265 | 0.065 |
| DHQ | 0.587 | 0.620 | 0.540 | -0.016 | 0.557 | 0.016 |
| DLQ | 1.520 | 1.760 | 1.460 | 0.107 | 1.459 | 0.040 |

TABLE 12: STATISTICS FOR BENICIA

derived from 28-day observation intervals

| 19-YEAR DATUM | MEAN | MAXIMUM | MINIMUM | REGRESSION PARAMETERS | | |
| --- | --- | --- | --- | --- | --- | --- |
| | | | | SLOPE | Y-INTERCEPT | STD DEVIATION |
| MHHW | 3.144 | 3.440 | 2.840 | 0.329 | 2.899 | 0.116 |
| MHW | 2.645 | 2.950 | 2.350 | 0.386 | 2.357 | 0.120 |
| MTL | 0.674 | 0.910 | 0.460 | 0.238 | 0.496 | 0.070 |
| MLW | -1.298 | -1.100 | -1.500 | 0.090 | -1.365 | 0.078 |
| MLLW | -2.522 | -2.280 | -2.870 | -0.123 | -2.440 | 0.148 |
| 19-YEAR RANGE | | | | | | |
| GR | 5.677 | 6.110 | 5.260 | 0.452 | 5.339 | 0.227 |
| MN | 3.943 | 4.260 | 3.720 | 0.296 | 3.722 | 0.142 |
| DHQ | 0.499 | 0.560 | 0.430 | -0.058 | 0.543 | 0.018 |
| DLQ | 1.234 | 1.420 | 1.060 | 0.213 | 1.075 | 0.057 |

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TABLE 15: STATISTICS FOR MALLARD ISLAND
derived from 28-day observation intervals

| 19-YEAR DATUM | MEAN | MAXIMUM | MINIMUM | REGRESSION PARAMETERS | | |
| --- | --- | --- | --- | --- | --- | --- |
| | | | | SLOPE | Y-INTERCEPT | STD DEVIATION |
| MHHW | 3.152 | 3.390 | 2.910 | 0.322 | 2.767 | 0.051 |
| MHW | 2.677 | 2.940 | 2.420 | 0.381 | 2.221 | 0.057 |
| MTL | 1.073 | 1.320 | 0.870 | 0.297 | 0.718 | 0.068 |
| MLW | -0.531 | -0.280 | -0.690 | 0.210 | -0.783 | 0.051 |
| MLLW | -1.455 | -1.080 | -1.640 | 0.095 | -1.568 | 0.057 |
| 19-YEAR RANGE | | | | | | |
| GR | 4.606 | 4.900 | 4.300 | 0.226 | 4.335 | 0.150 |
| MR | 3.207 | 3.400 | 3.070 | 0.169 | 3.005 | 0.073 |
| DHQ | 0.475 | 0.520 | 0.400 | -0.059 | 0.546 | 0.017 |
| DLQ | 0.524 | 1.060 | 0.740 | 0.116 | 0.735 | 0.052 |

TABLE 14: STATISTICS FOR THREE MILE SLOUGH
derived from 28-day observation intervals

| 19-YEAR DATUM | MEAN | MAXIMUM | MINIMUM | REGRESSION PARAMETERS | | |
|---|---|---|---|---|---|---|
| | | | | SLOPE | Y-INTERCEPT | STD DEVIATION |
| MHHW | 3.446 | 3.780 | 3.010 | 0.491 | 2.742 | 0.145 |
| MHW | 2.992 | 3.340 | 2.560 | 0.512 | 2.259 | 0.138 |
| MTL | 1.348 | 1.700 | 0.940 | 0.514 | 0.612 | 0.115 |
| MLW | -0.251 | 0.110 | -0.690 | 0.514 | -1.034 | 0.104 |
| MLLW | -1.181 | -0.780 | -1.490 | 0.422 | -1.787 | 0.058 |
| 19-YEAR RANGE | | | | | | |
| GR | 4.626 | 4.550 | 4.410 | 0.665 | 4.527 | 0.144 |
| MN | 3.285 | 3.540 | 3.170 | -0.002 | 3.292 | 0.082 |
| DHQ | 0.453 | 0.500 | 0.380 | -0.021 | 0.484 | 0.010 |
| DLQ | 0.884 | 1.030 | 0.760 | 0.052 | 0.752 | 0.005 |

TABLE 15: STATISTICS FOR WALNUT GROVE

derived from 28-day observation intervals

| 19-YEAR DATUM | MEAN | MAXIMUM | MINIMUM | REGRESSION PARAMETERS | | |
| --- | --- | --- | --- | --- | --- | --- |
| | | | | SLOPE | Y-INTERCEPT | STD DEVIATION |
| MHHW | 3.868 | 6.270 | 3.110 | 0.724 | 2.098 | 0.135 |
| MHW | 3.481 | 6.260 | 2.730 | 0.786 | 1.559 | 0.129 |
| ATL | 2.441 | 5.610 | 1.640 | 0.914 | 0.205 | 0.125 |
| MLW | 1.401 | 4.950 | 0.540 | 1.042 | -1.148 | 0.134 |
| MLLW | 0.988 | 4.850 | 0.050 | 1.120 | -1.751 | 0.116 |
| 19-YEAR RANGE | | | | | | |
| GR | 2.880 | 3.240 | 1.380 | -0.396 | 3.848 | 0.107 |
| MN | 2.080 | 2.370 | 1.310 | -0.256 | 2.707 | 0.075 |
| DHQ | 0.367 | 0.470 | 0.0 | -0.063 | 0.540 | 0.045 |
| DLQ | 0.413 | 0.530 | 0.060 | -0.077 | 0.602 | 0.055 |

TABLE 16: STATISTICS FOR SACRAMENTO FROM A 7-DAY COMPARISON

| 19-YEAR DATUM | MEAN | MAXIMUM | MINIMUM | REGRESSION PARAMETERS | | |
|---|---|---|---|---|---|---|
| | | | | SLOPE | Y-INTERCEPT | STD DEVIATION |
| MHHW | 7.411 | 22.310 | 3.570 | 0.932 | 0.986 | 0.259 |
| MHW | 7.165 | 22.270 | 3.710 | 0.940 | 0.685 | 0.206 |
| MTL | 6.844 | 22.240 | 3.190 | 0.970 | 0.155 | 0.212 |
| MLW | 6.522 | 22.240 | 2.570 | 1.001 | -0.377 | 0.259 |
| MLLW | 6.372 | 22.220 | 2.140 | 1.000 | -0.524 | 0.282 |
| 15-YEAR RANGE | | | | | | |
| GR | 1.035 | 2.960 | 0.0 | -0.068 | 1.510 | 0.210 |
| MN | 0.643 | 1.430 | 0.0 | -0.061 | 1.063 | 0.159 |
| DHQ | 0.241 | 1.260 | 0.0 | -0.068 | 0.301 | 0.163 |
| DLQ | 0.150 | 1.040 | 0.0 | 0.0 | 0.147 | 0.155 |

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TABLE 17: STATISTICS FOR SACRAMENTO FROM A 14-DAY COMPARISON

| 19-YEAR DATUM | MEAN | MAXIMUM | MINIMUM | REGRESSION PARAMETERS | | |
| --- | --- | --- | --- | --- | --- | --- |
| | | | | SLOPE | Y-INTERCEPT | STD DEVIATION |
| MHHW | 7.465 | 21.410 | 4.110 | 0.927 | 1.005 | 0.211 |
| MHW | 7.233 | 21.400 | 3.810 | 0.939 | 0.689 | 0.177 |
| MTL | 6.917 | 21.400 | 3.320 | 0.965 | 0.165 | 0.176 |
| MLW | 6.600 | 21.400 | 2.780 | 0.998 | -0.359 | 0.215 |
| MLLW | 6.475 | 21.380 | 2.520 | 1.002 | -0.507 | 0.214 |
| 19-YEAR RANGE | | | | | | |
| GR | 0.556 | 1.660 | 0.010 | -0.075 | 1.512 | 0.232 |
| AN | 0.633 | 1.100 | 0.0 | -0.660 | 1.048 | 0.175 |
| DHQ | 0.232 | 0.820 | 0.0 | -0.012 | 0.316 | 0.104 |
| DLQ | 0.125 | 0.710 | 0.0 | -0.003 | 0.143 | 0.054 |

TABLE 18: STATISTICS FOR SACRAMENTO FROM A 28-DAY COMPARISON

| | | | | REGRESSION PARAMETERS | | |
|---|---|---|---|---|---|---|
| 19-YEAR DATUM | MEAN | MAXIMUM | MINIMUM | SLOPE | Y-INTERCEPT | STD DEVIATION |
| MHHW | 7.356 | 17.270 | 4.140 | 0.922 | 1.037 | 0.134 |
| MHW | 7.172 | 17.270 | 3.850 | 0.938 | 0.700 | 0.128 |
| MTL | 6.851 | 17.170 | 3.350 | 0.967 | 0.176 | 0.137 |
| MLW | 6.530 | 17.140 | 2.840 | 0.991 | -0.348 | 0.180 |
| MLLW | 6.422 | 17.060 | 2.660 | 1.006 | -0.516 | 0.165 |
| 19-YEAR RANGE | | | | | | |
| GR | 0.574 | 1.550 | 0.150 | -0.084 | 1.553 | 0.176 |
| MN | 0.642 | 1.030 | 0.0 | -0.055 | 1.047 | 0.154 |
| DHQ | 0.224 | 0.480 | 0.0 | -0.016 | 0.337 | 0.070 |
| DLQ | 0.168 | 0.360 | 0.0 | -0.009 | 0.168 | 0.063 |

TABLE 19: STATISTICS FOR SACRAMENTO FROM A 56-DAY COMPARISON

| 19-YEAR DATUM | MEAN | MAXIMUM | MINIMUM | REGRESSION PARAMETERS | | |
|---|---|---|---|---|---|---|
| | | | | SLOPE | Y-INTERCEPT | STD DEVIATION |
| MHHW | 7.254 | 15.600 | 4.380 | 0.917 | 1.054 | 0.100 |
| MHW | 7.036 | 15.600 | 4.100 | 0.938 | 0.695 | 0.096 |
| MTL | 6.717 | 15.470 | 3.640 | 0.970 | 0.155 | 0.105 |
| MLW | 6.399 | 15.340 | 3.170 | 1.003 | -0.385 | 0.142 |
| MLLW | 6.303 | 15.340 | 3.000 | 1.014 | -0.553 | 0.134 |
| 19-YEAR RANGE | | | | | | |
| GR | 0.951 | 1.450 | 0.180 | -0.097 | 1.607 | 0.118 |
| MN | 0.637 | 0.970 | 0.020 | -0.066 | 1.080 | 0.104 |
| DHQ | 0.218 | 0.430 | 0.0 | -0.021 | 0.359 | 0.049 |
| DLQ | 0.096 | 0.250 | 0.0 | -0.011 | 0.168 | 0.049 |

Table 20. REGRESSION STATISTICS FOR 28-DAY MEAN RIVER LEVELS AT RIVER STATIONS RELATIVE TO 28-DAY MEAN RIVER LEVELS AT SACRAMENTO.

| STATION | Y-INTERCEPT | SLOPE | STANDARD DEVIATION |
|---|---|---|---|
| POINT ORIENT | 0.114 NGVD | 0.053 | 0.142 FEET |
| BENICIA | 0.215 | 0.066 | 0.162 |
| MALLARD ISLAND | 0.095 | 0.109 | 0.213 |
| THREE MILE SLOUGH | 0.044 | 0.164 | 0.145 |
| WALNUT GROVE | 0.023 | 0.408 | 0.110 |

EXAMPLE: MRL(Walnut Grove) = 0.408 x MRL(Sacramento) + 0.023

(see Figure 25)

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Figure 1: LOWER SACRAMENTO RIVER SYSTEM

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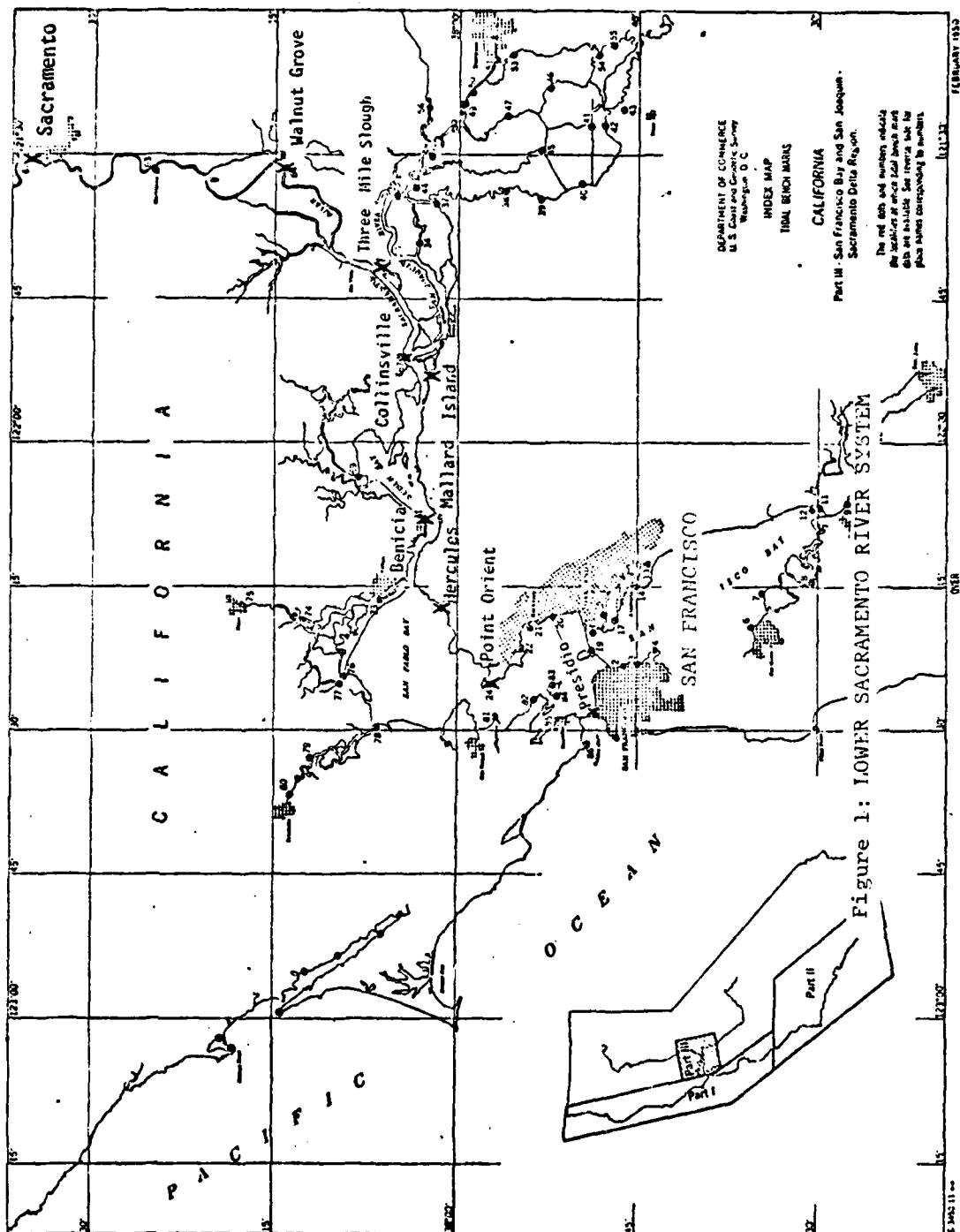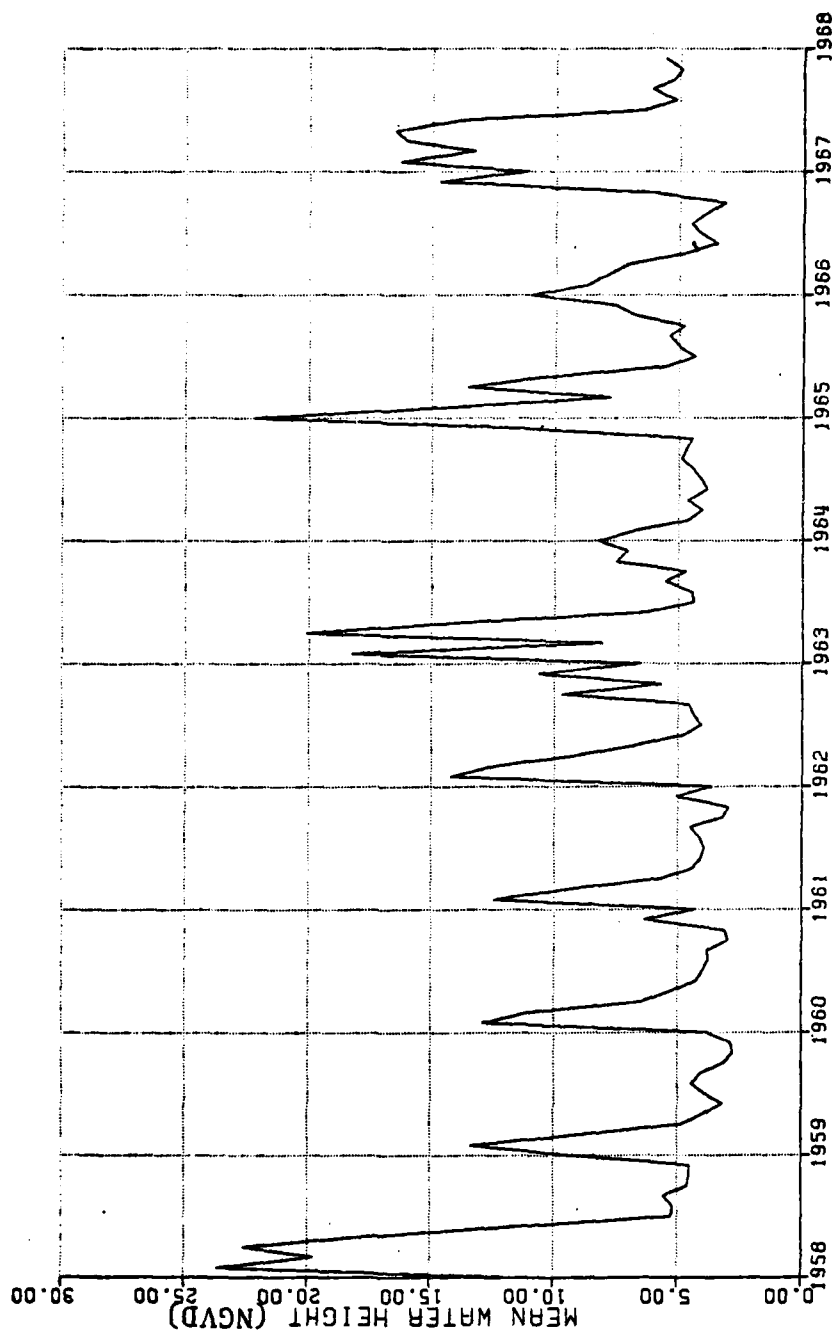
Figure 2A. MONTHLY MEAN RIVER LEVEL AT SACRAMENTO

78
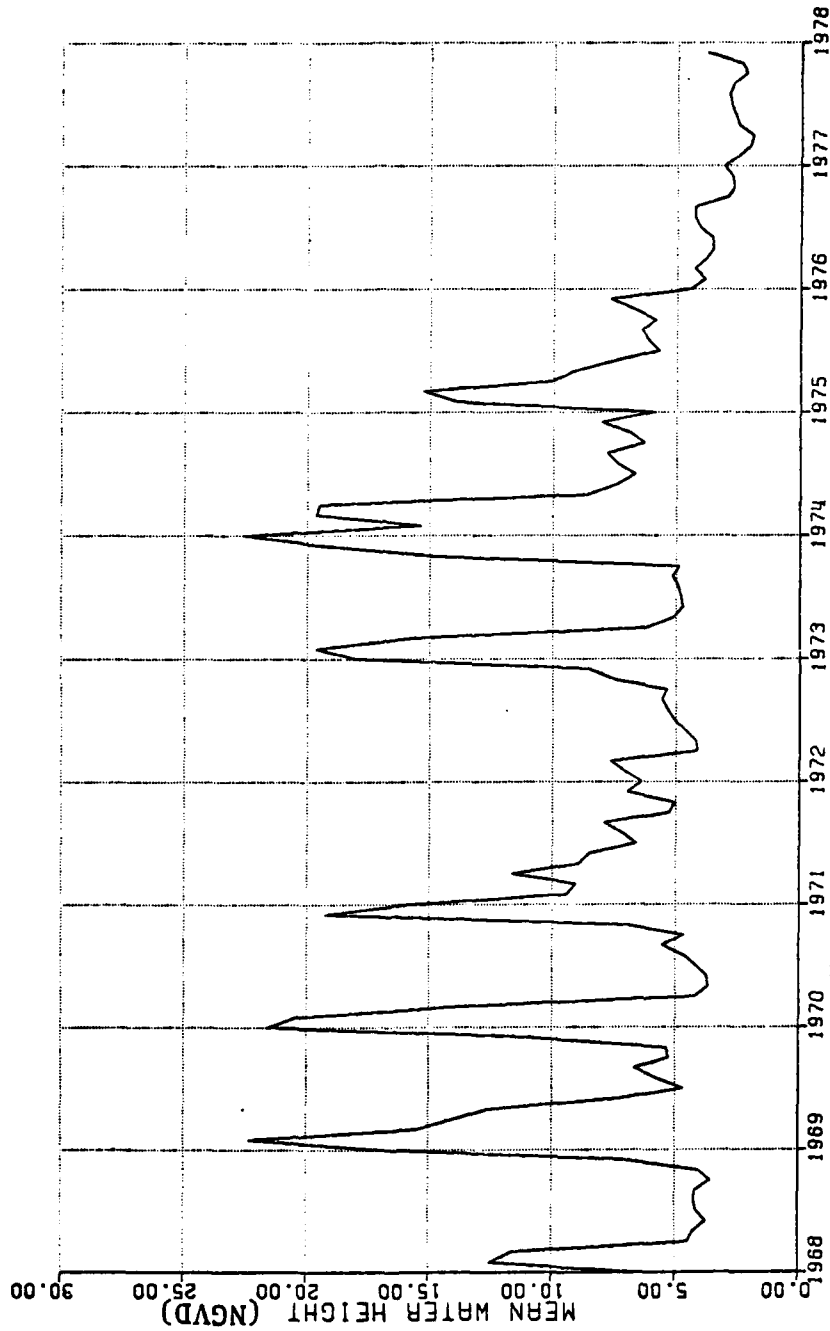
Figure 2B.  MONTHLY MEAN RIVER LEVEL AT SACRAMENTO

79
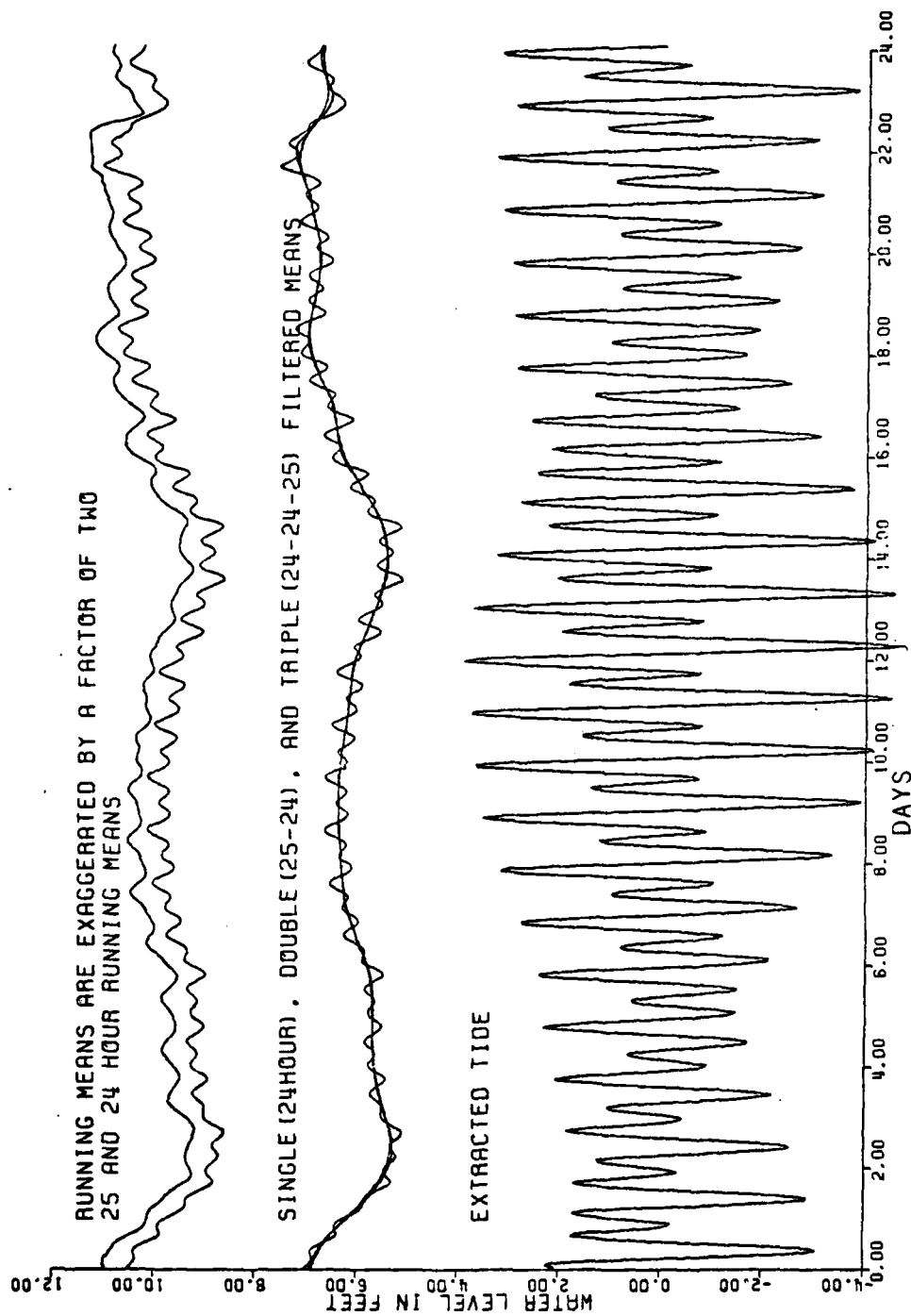
Figure 3.  FILTERED RUNNING MEANS AND EXTRACTED TIDE AT PRESIDIO
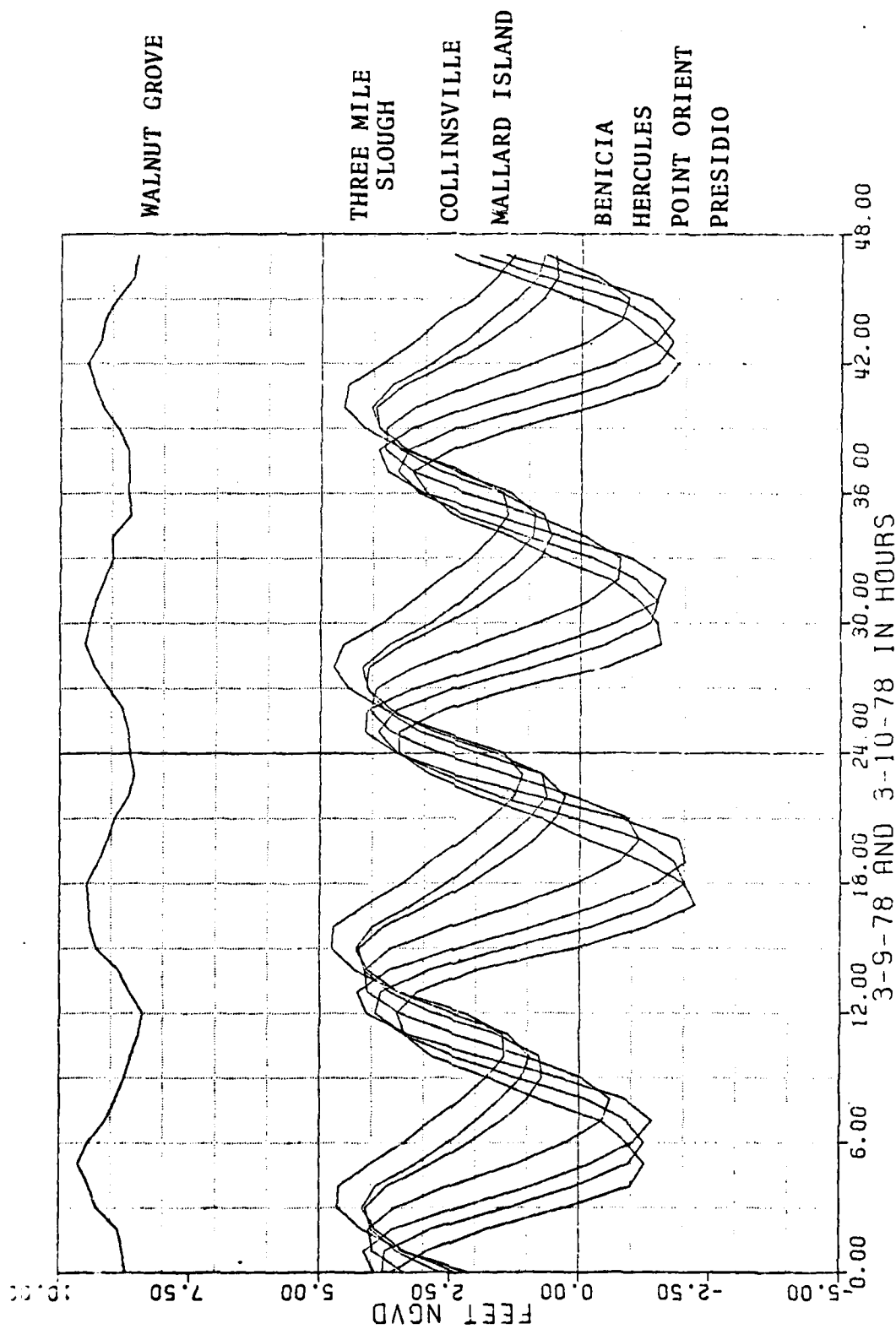
Figure 4. SIMULTANEOUS WATER LEVELS AT HIGH WATER IN THE SACRAMENTO RIVER

81
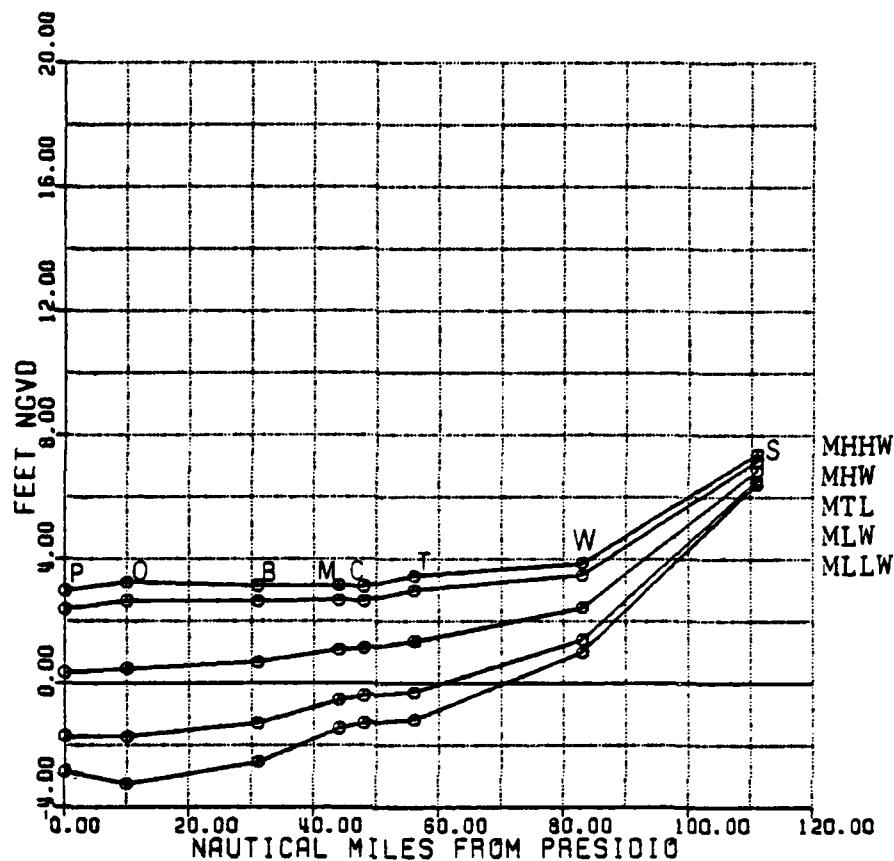
Figure 5. MEAN 19-YEAR TIDAL DATUMS ALONG THE SACRAMENTO
RIVER SYSTEM FROM 28-DAY COMPARISONS OVER THE STUDY PERIOD.
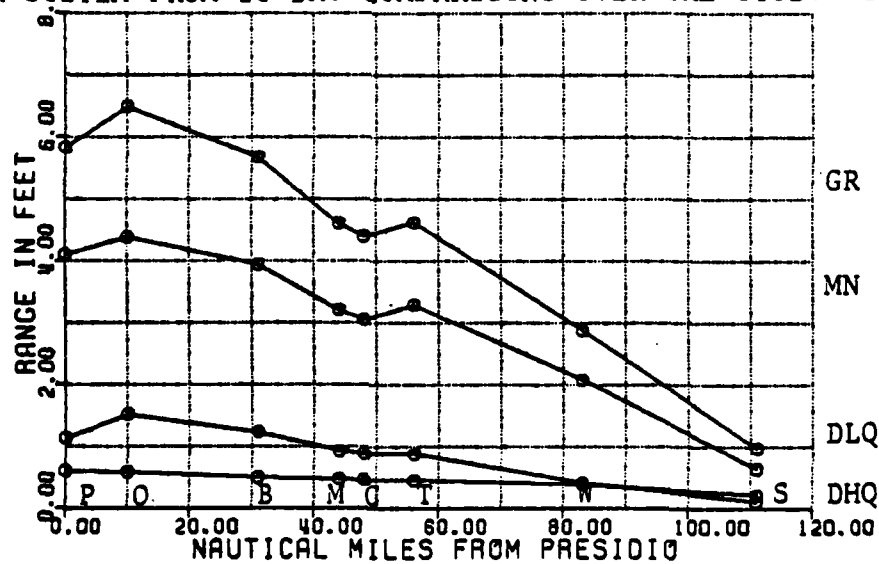


Figure 6. MEAN 19-YEAR TIDAL RANGES ALONG THE SACRAMENTO
RIVER SYSTEM FROM 28-DAY COMPARISONS OVER THE STUDY PERIOD.
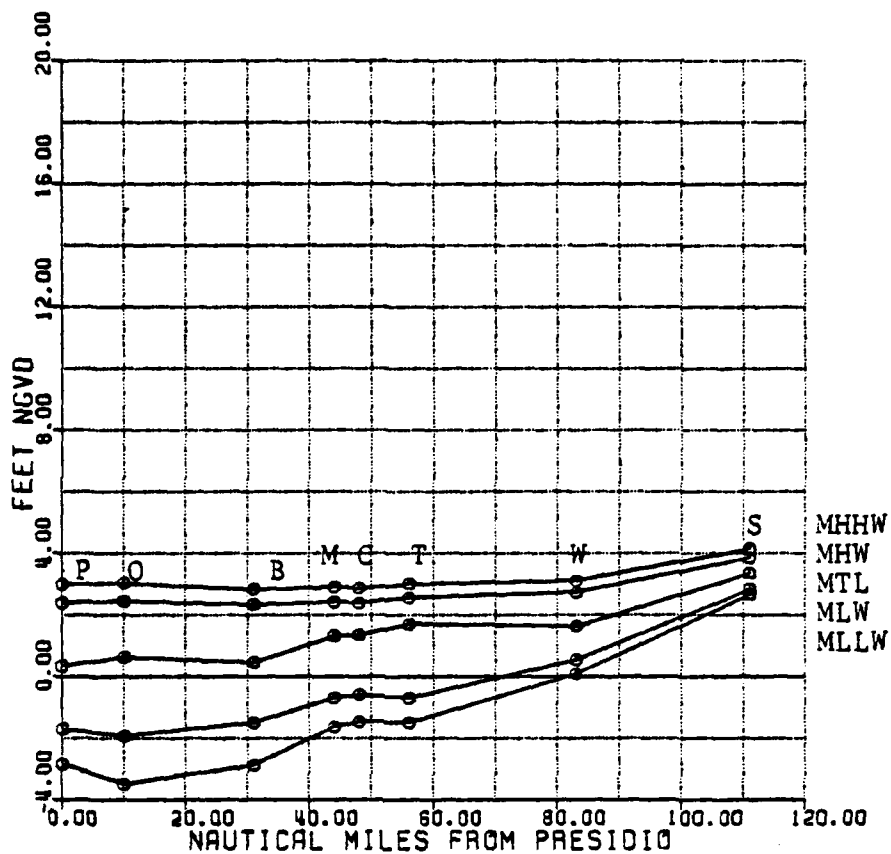
Figure 7.    19-YEAR TIDAL DATUMS AT LOW WATER ALONG THE
SACRAMENTO RIVER SYSTEM FROM 28-DAY COMPARISONS
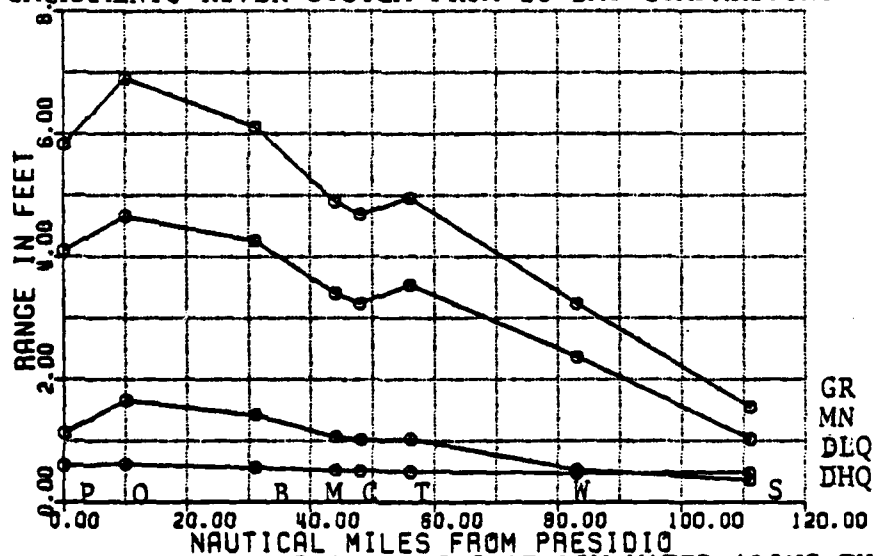


Figure 8.    19-YEAR TIDAL RANGES AT LOW WATER ALONG THE
SACRAMENTO RIVER SYSTEM FROM 28-DAY COMPARISONS

83
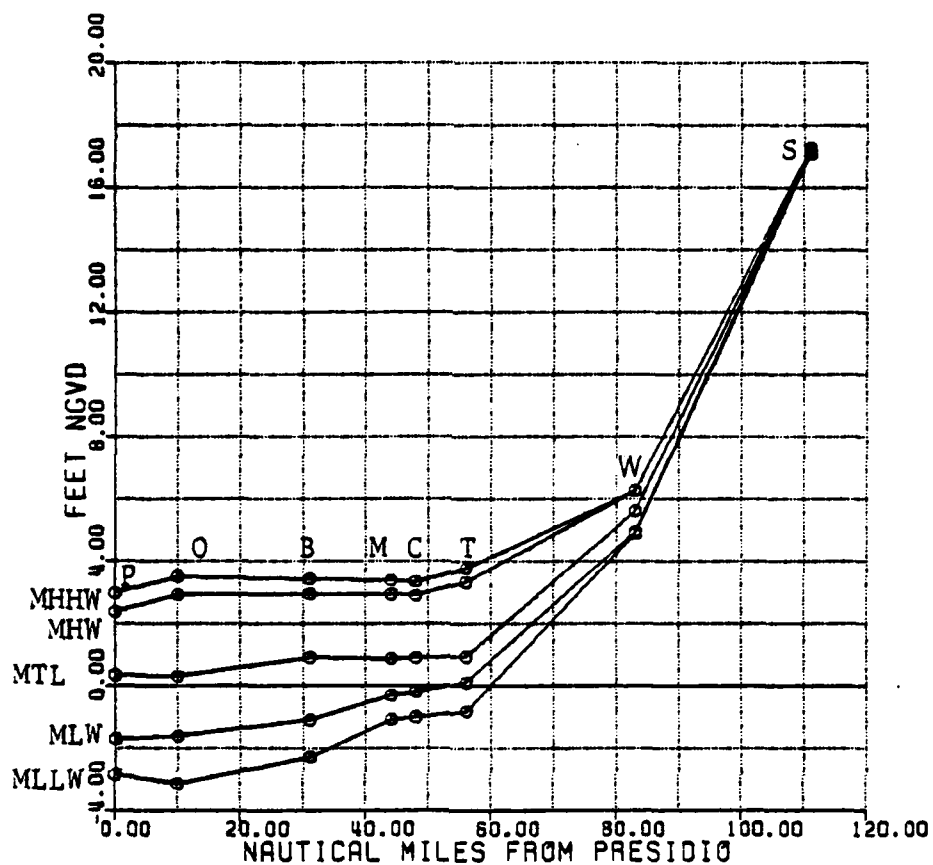
Figure 9.  19-YEAR TIDAL DATUMS AT HIGH WATER ALONG THE
SACRAMENTO RIVER SYSTEM FROM 28-DAY COMPARISONS
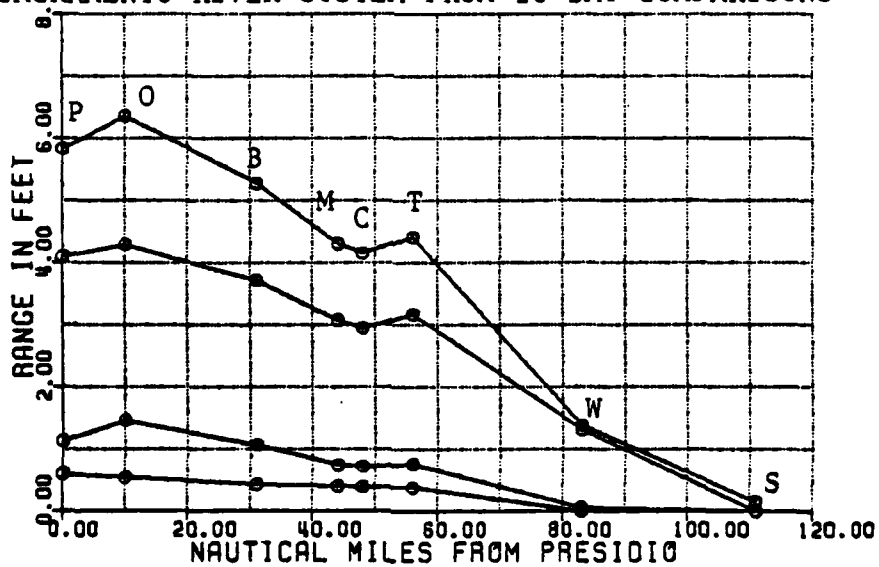


Figure 10.  19-YEAR TIDAL RANGES AT HIGH WATER ALONG THE
SACRAMENTO RIVER SYSTEM FROM 28-DAY COMPARISONS

84
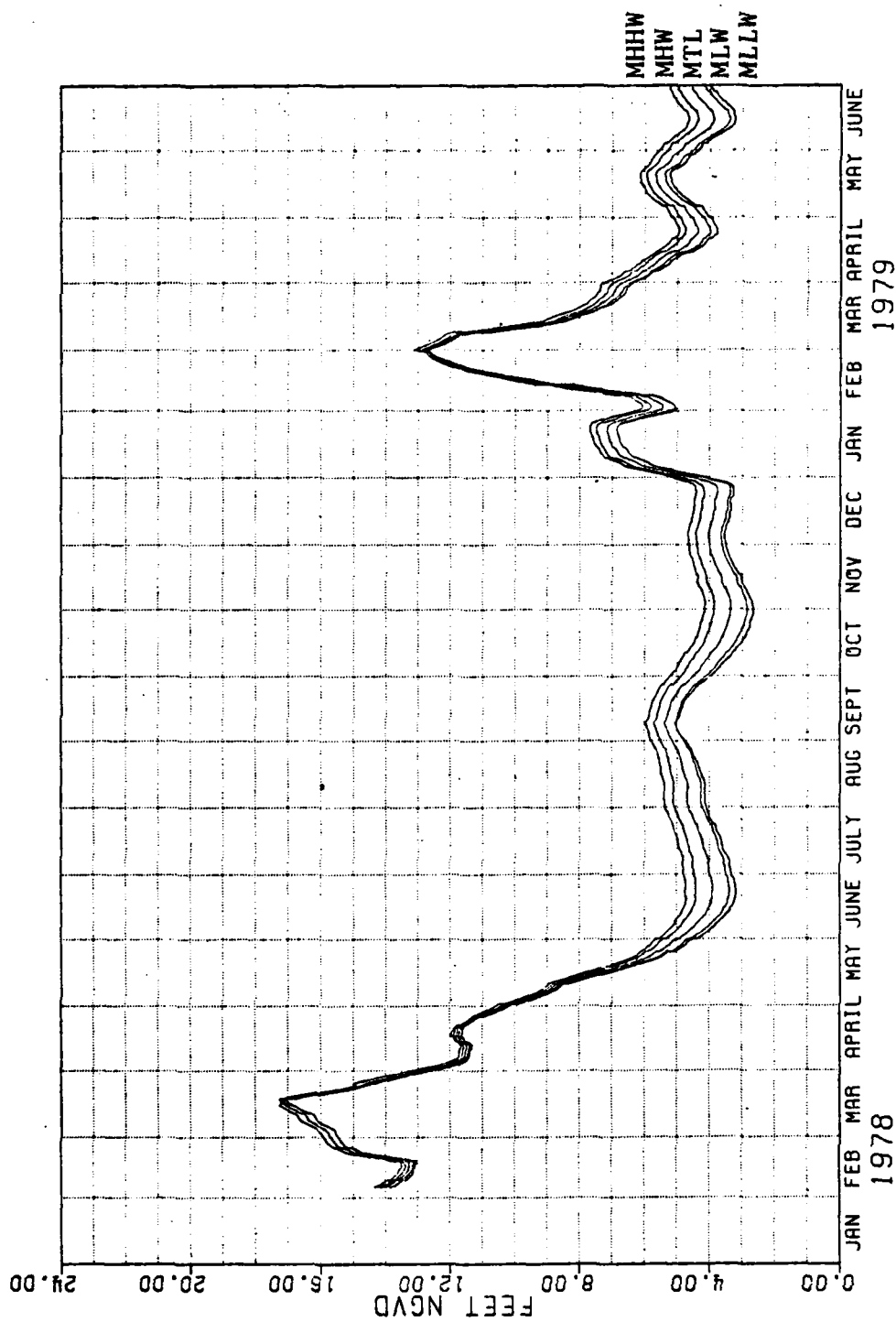
Figure 11. 19-YEAR TIDAL DATUMS AT SACRAMENTO COMPUTED WITH 28-DAY COMPARISONS

85
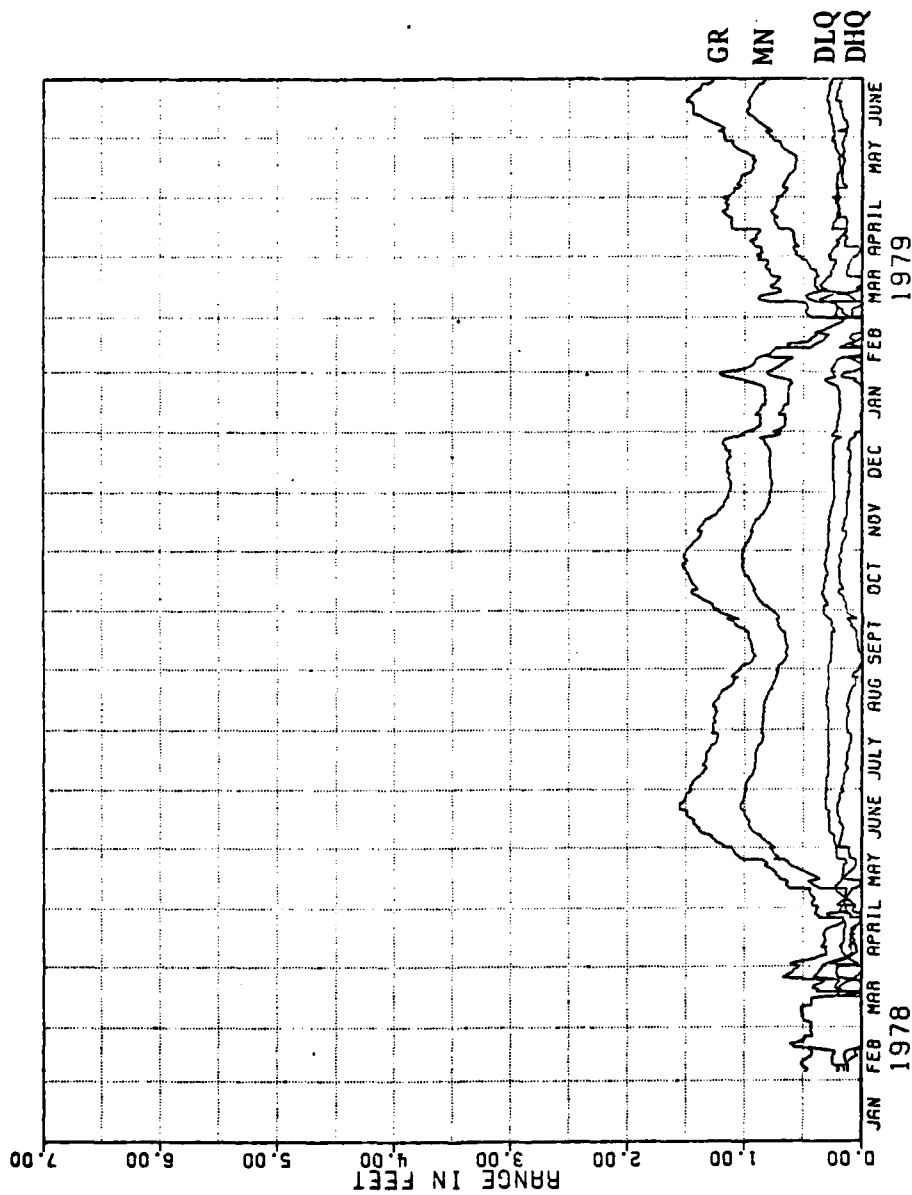
Figure 12. 19-YEAR TIDAL RANGES AT SACRAMENTO COMPUTED FROM 28-DAY COMPARISONS

86
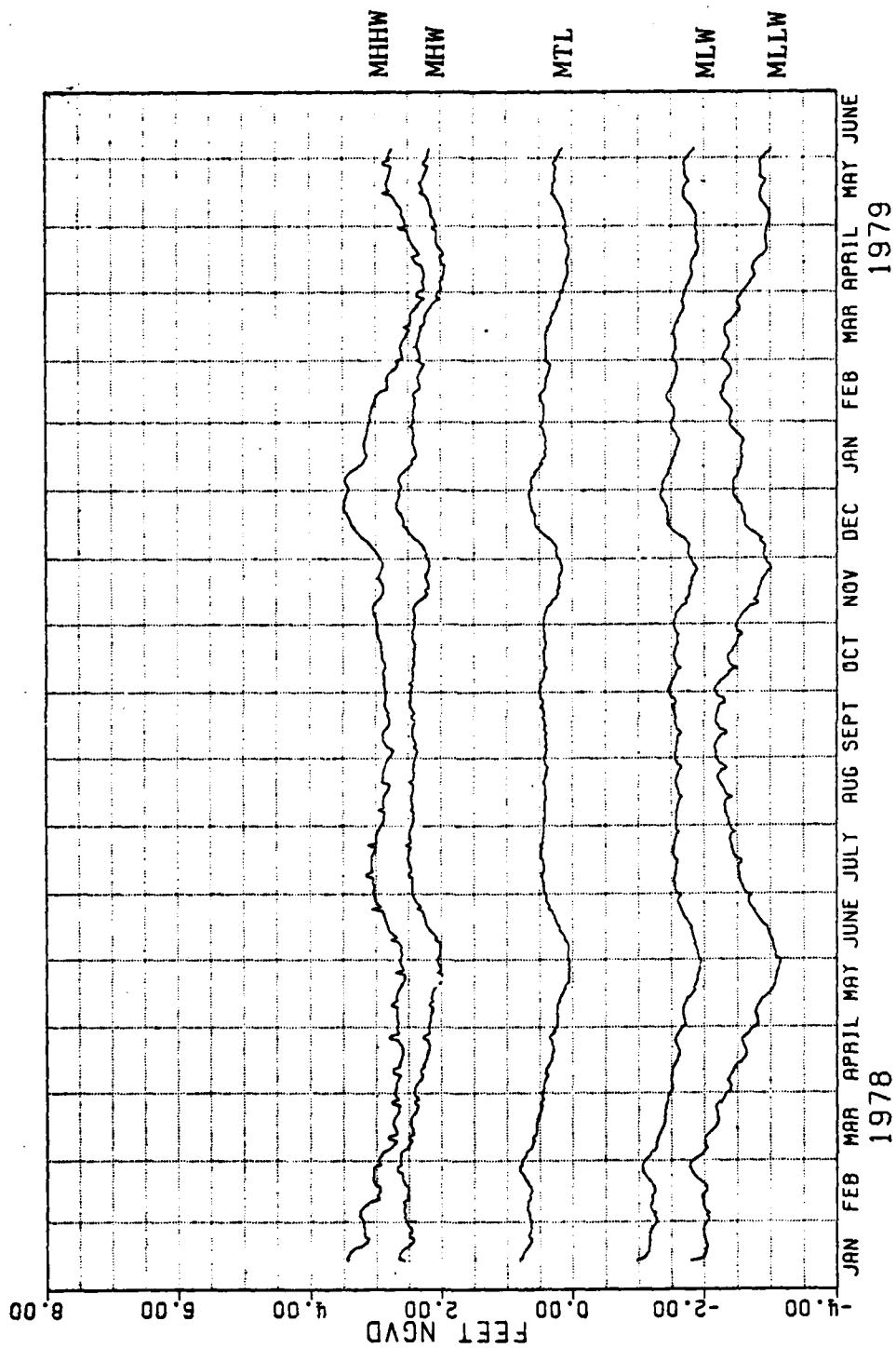
Figure 13. TIDAL DATUMS AT PRESIDIO FOR THE STUDY PERIOD
COMPUTED WITH A 28-DAY RUNNING MEAN

87
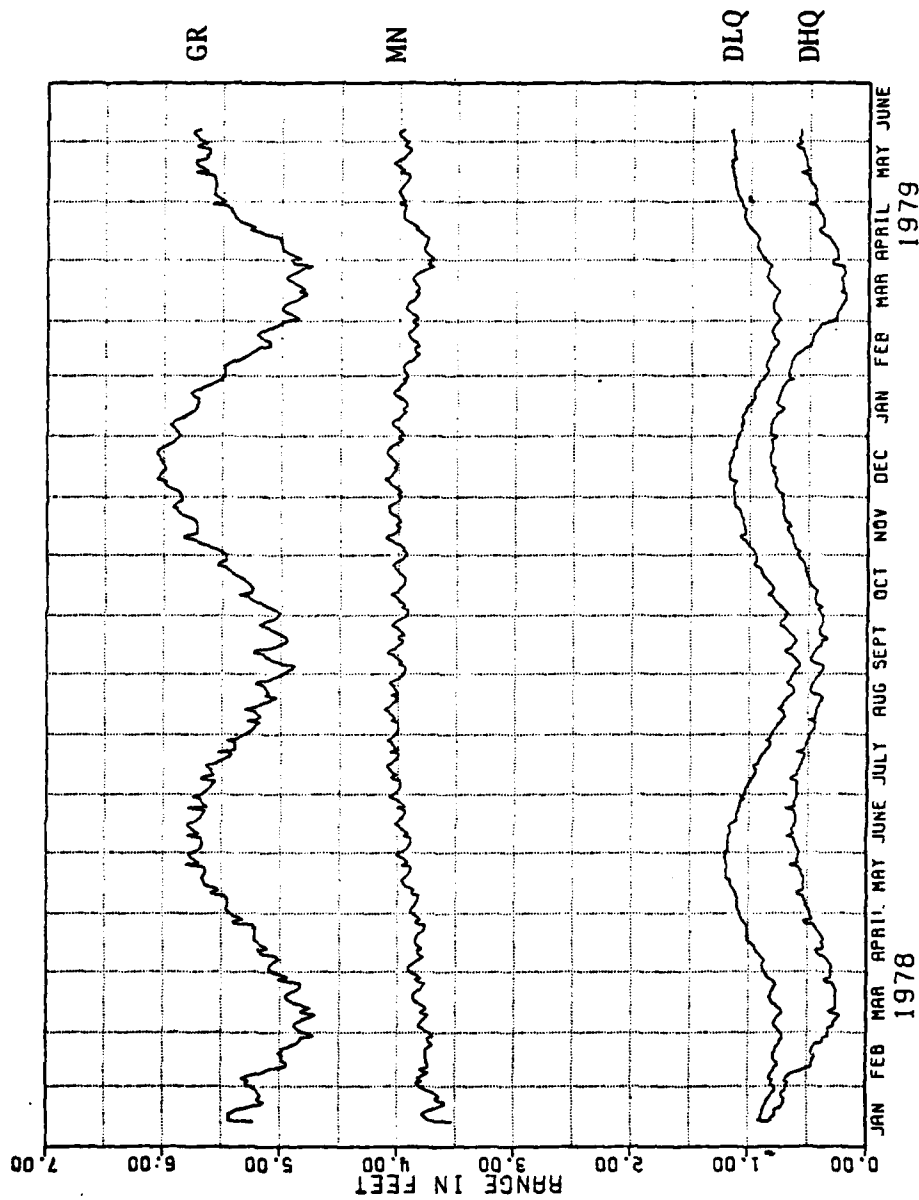
Figure 14. TIDAL RANGES AT PRESIDIO COMPUTED WITH A 28-DAY RUNNING MEAN
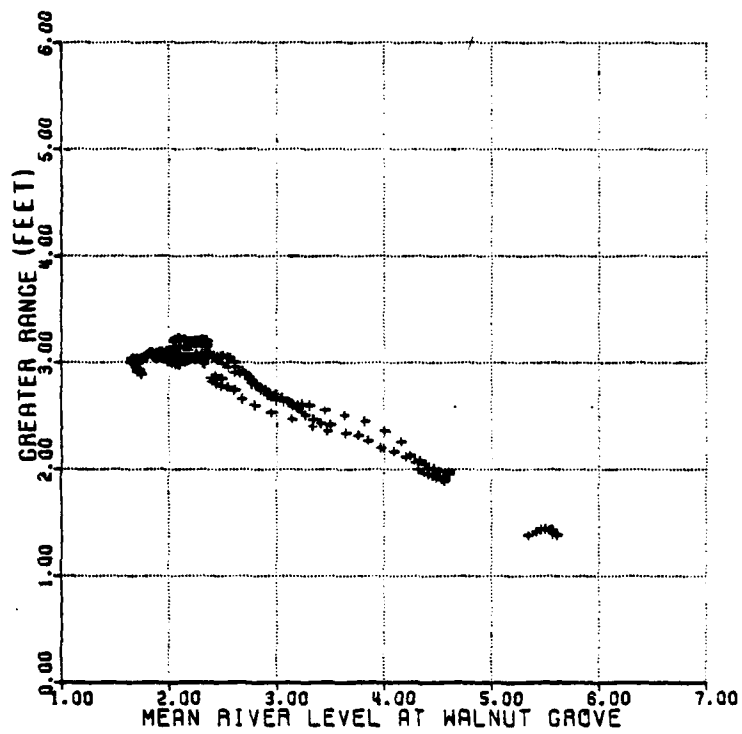
Figure 15: 19-YEAR GREATER RANGE RELATIVE
TO MEAN RIVER LEVEL (NGVD) FROM
28-DAY COMPARISONS OVER THE STUDY
PERIOD AT WALNUT GROVE.
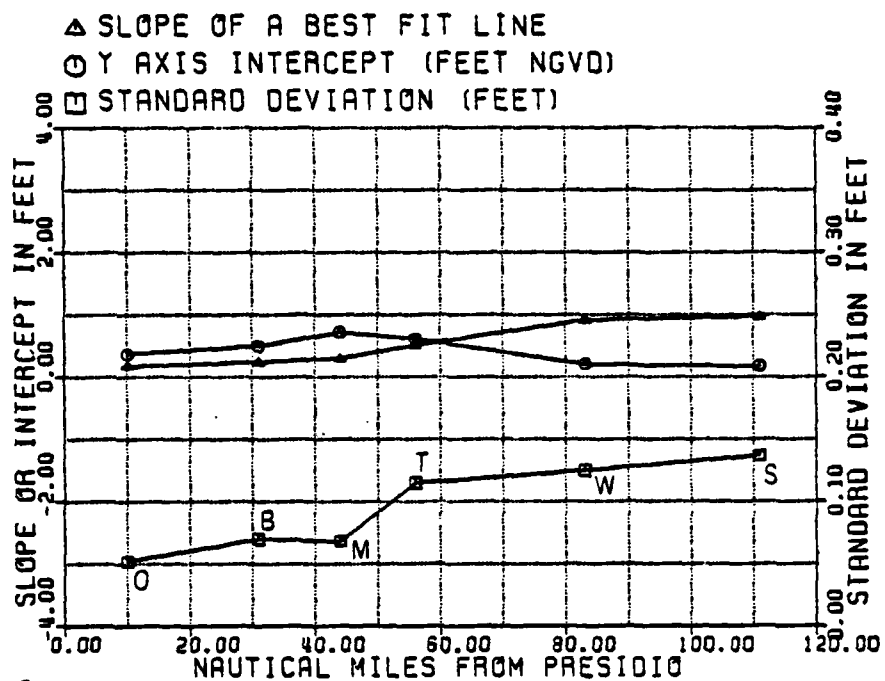
Figure 16. VARIABILITY OF 19-YEAR MEAN TIDE LEVELS
RELATIVE TO MEAN RIVER LEVELS FROM
28-DAY OBSERVATIONS OVER THE STUDY
PERIOD.

90
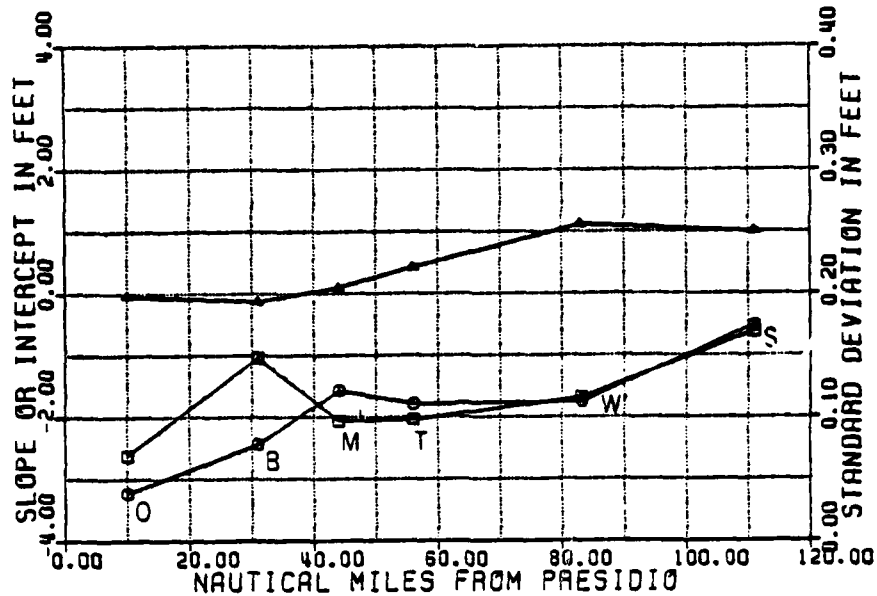
Figure 17.   VARIABILITY OF 19-YEAR MEAN LOWER LOW
WATERS RELATIVE TO MEAN RIVER LEVELS
FROM 28-DAY OBSERVATIONS OVER THE
STUDY PERIOD.

△ SLOPE OF A BEST FIT LINE
⊙ Y AXIS INTERCEPT (FEET NGVD)
▫ STANDARD DEVIATION (FEET)
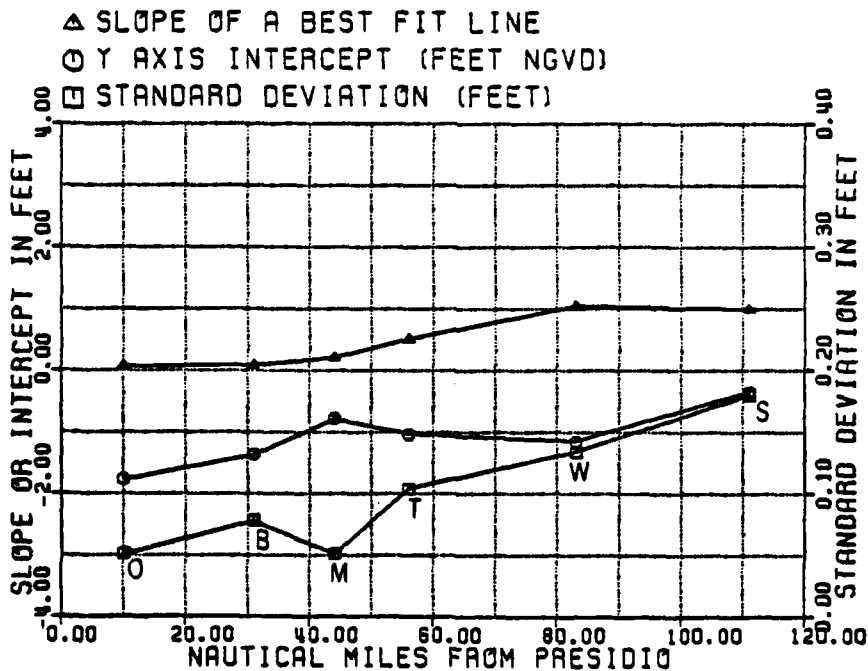


Figure 18.   VARIABILITY OF 19-YEAR MEAN LOW WATERS
RELATIVE TO MEAN RIVER LEVELS FROM 28-
DAY OBSERVATIONS OVER THE STUDY PERIOD.

91
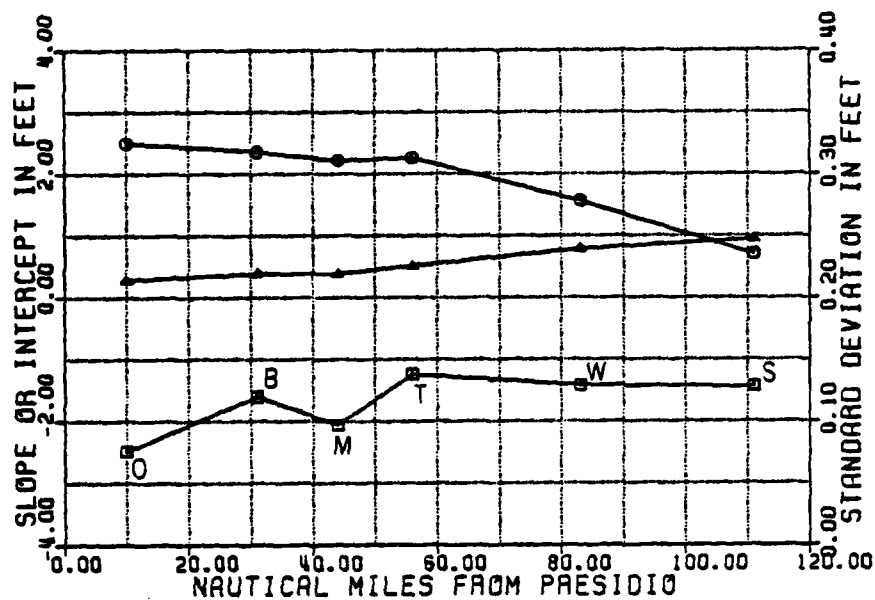
Figure 19.   VARIABILITY OF 19-YEAR MEAN HIGH WATERS
             RELATIVE TO MEAN RIVER LEVELS FROM
             28-DAY OBSERVATIONS OVER THE
             STUDY PERIOD.

△ SLOPE OF A BEST FIT LINE
⊙ Y AXIS INTERCEPT (FEET NGVD)
▣ STANDARD DEVIATION (FEET)
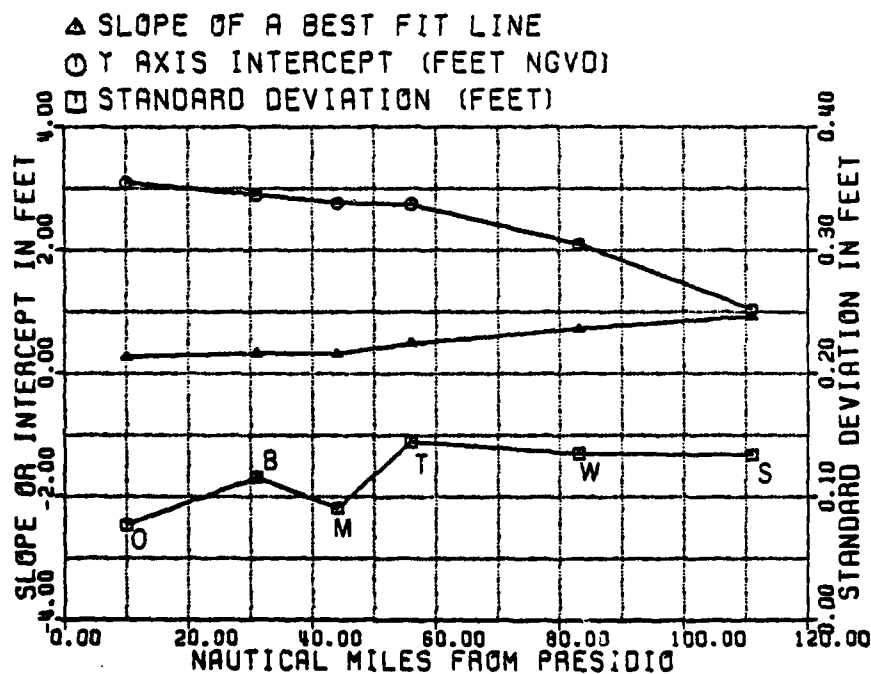


Figure 20.   VARIABILITY OF 19-YEAR MEAN HIGHER HIGH
             WATERS RELATIVE TO MEAN RIVER LEVELS
             FROM 28-DAY OBSERVATIONS OVER THE
             STUDY PERIOD.

92
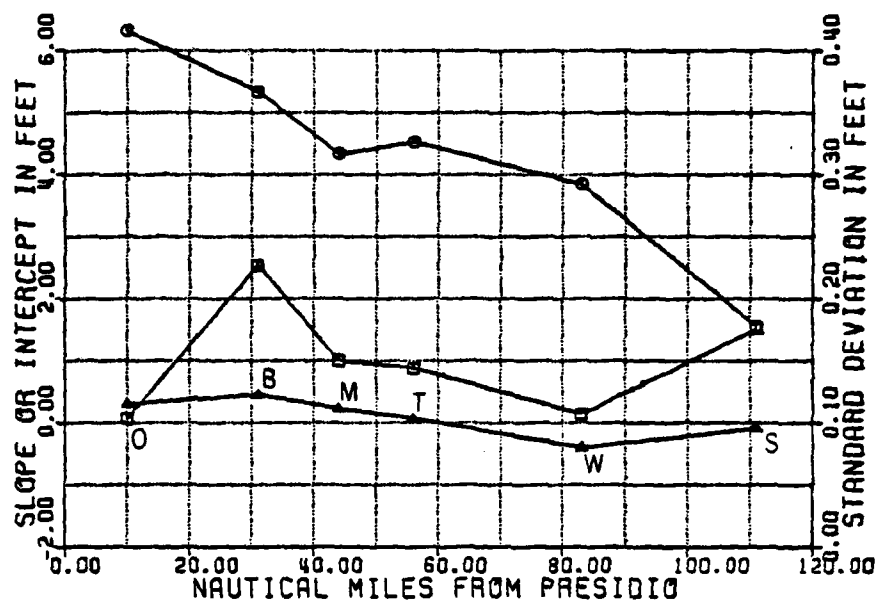
Figure 21.   VARIABILITY OF 19-YEAR GREATER RANGES
RELATIVE TO MEAN RIVER LEVELS FROM
28-DAY OBSERVATIONS OVER THE STUDY
PERIOD.

△ SLOPE OF A BEST FIT LINE
⊙ Y AXIS INTERCEPT (FEET NGVD)
□ STANDARD DEVIATION (FEET)
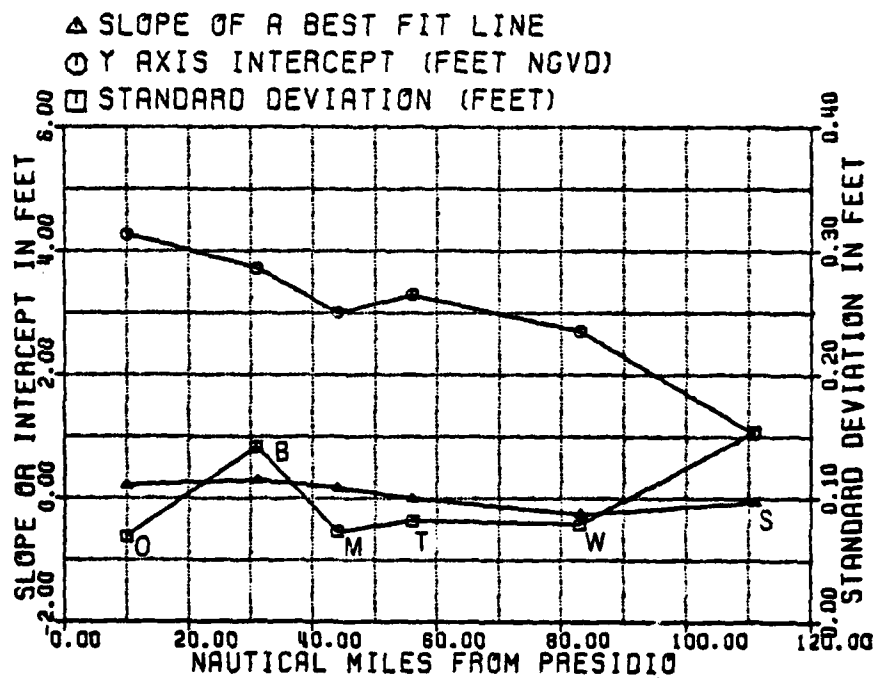


Figure 22.   VARIABILITY OF 19-YEAR MEAN RANGE
RELATIVE TO MEAN RIVER LEVELS FROM
28-DAY OBSERVATIONS OVER THE STUDY
PERIOD.
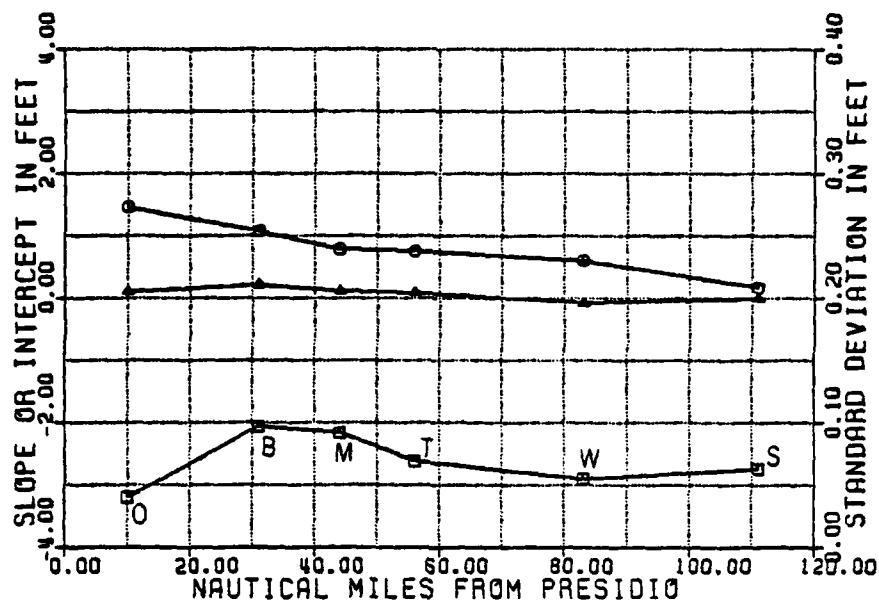
Figure 23.   VARIABILITY OF 19-YEAR DIURNAL LOW
             INEQUALITIES RELATIVE TO MEAN RIVER
             LEVELS FROM 28-DAY OBSERVATIONS
             OVER THE STUDY PERIOD.

△ SLOPE OF A BEST FIT LINE
⊙ Y AXIS INTERCEPT (FEET NGVD)
⊡ STANDARD DEVIATION (FEET)
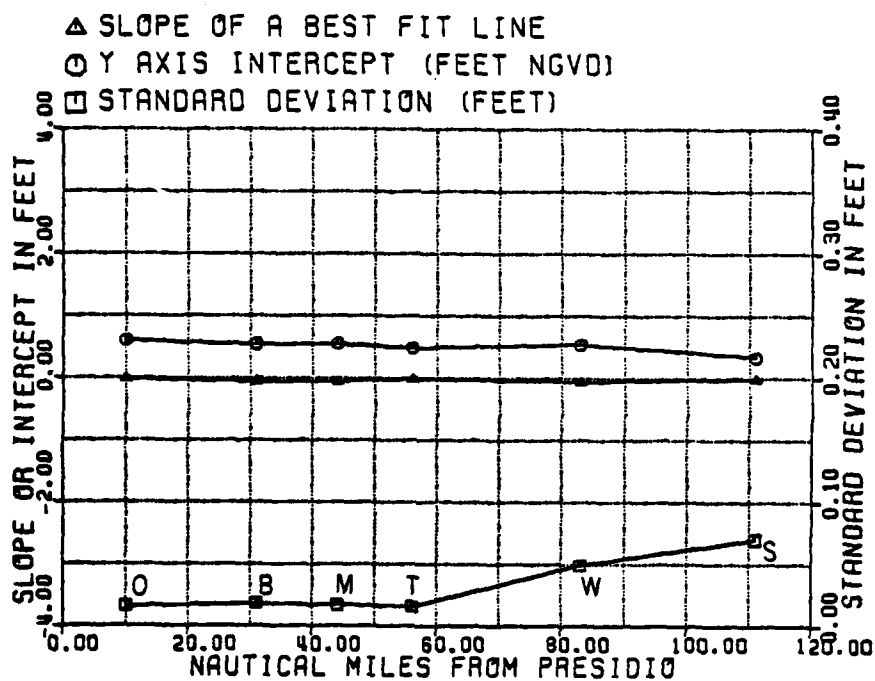


Figure 24.   VARIABILITY OF 19-YEAR DIURNAL  HIGH
             INEQUALITIES RELATIVE TO MEAN RIVER
             LEVELS FROM 28-DAY OBSERVATIONS OVER
             THE STUDY PERIOD.

94
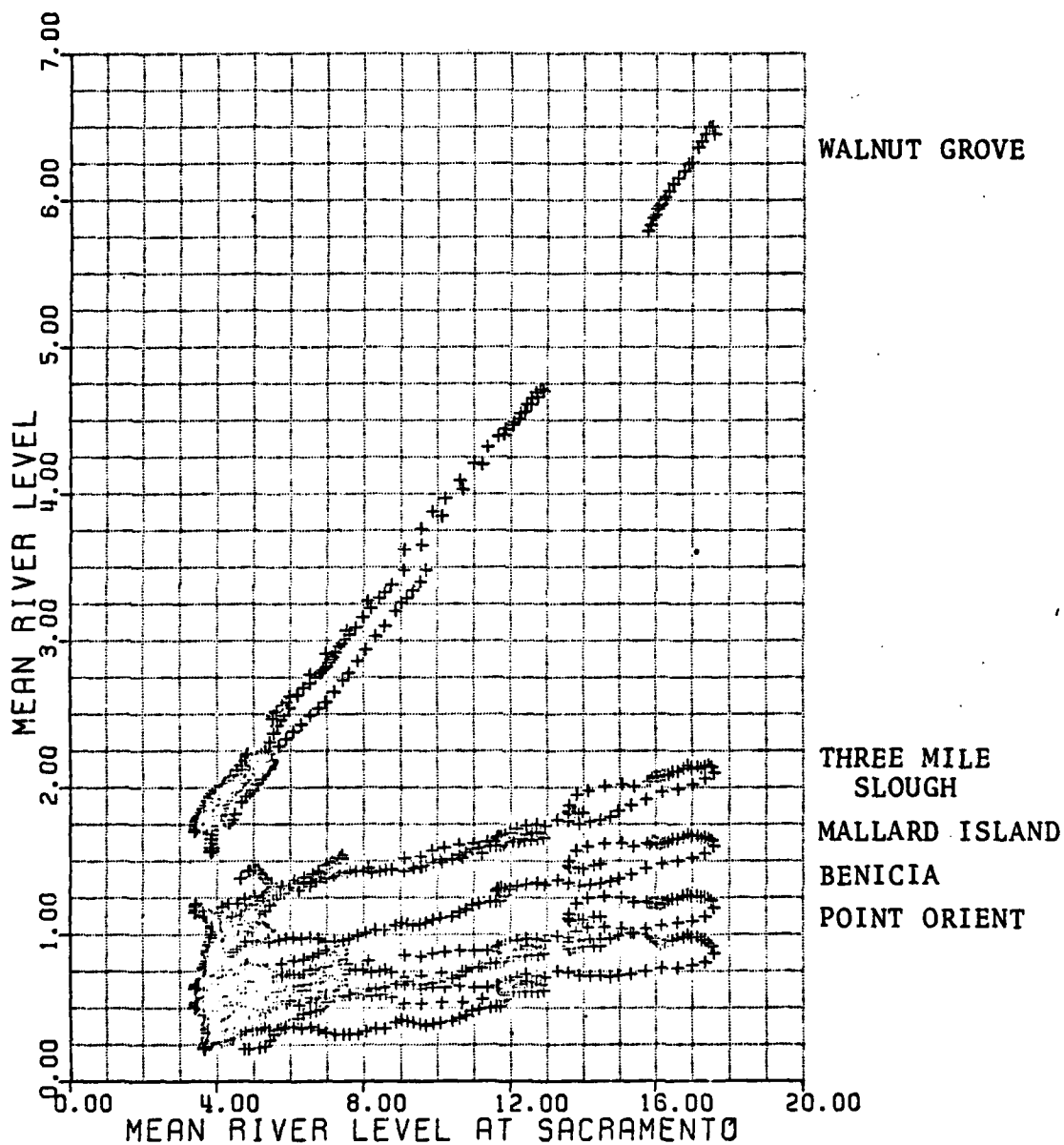
Figure 25. RELATION BETWEEN MEAN RIVER LEVEL (NGVD) AT
SACRAMENTO AND AT OTHER RIVER STATIONS FROM
28-DAY OBSERVATIONS OVER THE STUDY PERIOD.
SEE FIGURE 20.

95
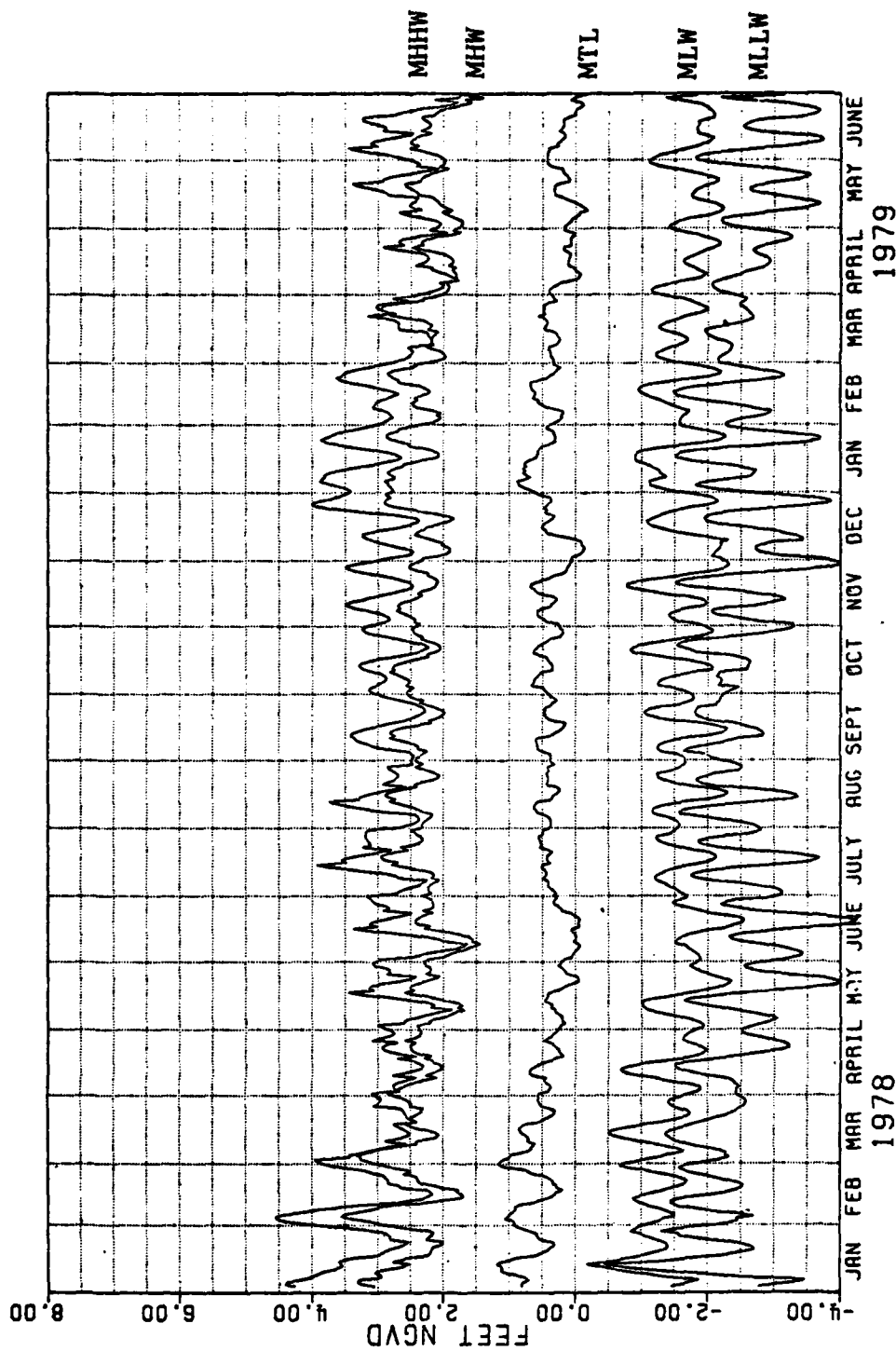
Figure 26. TIDAL DATUMS AT PRESIDIO COMPUTED WITH A 7-DAY RUNNING MEAN.
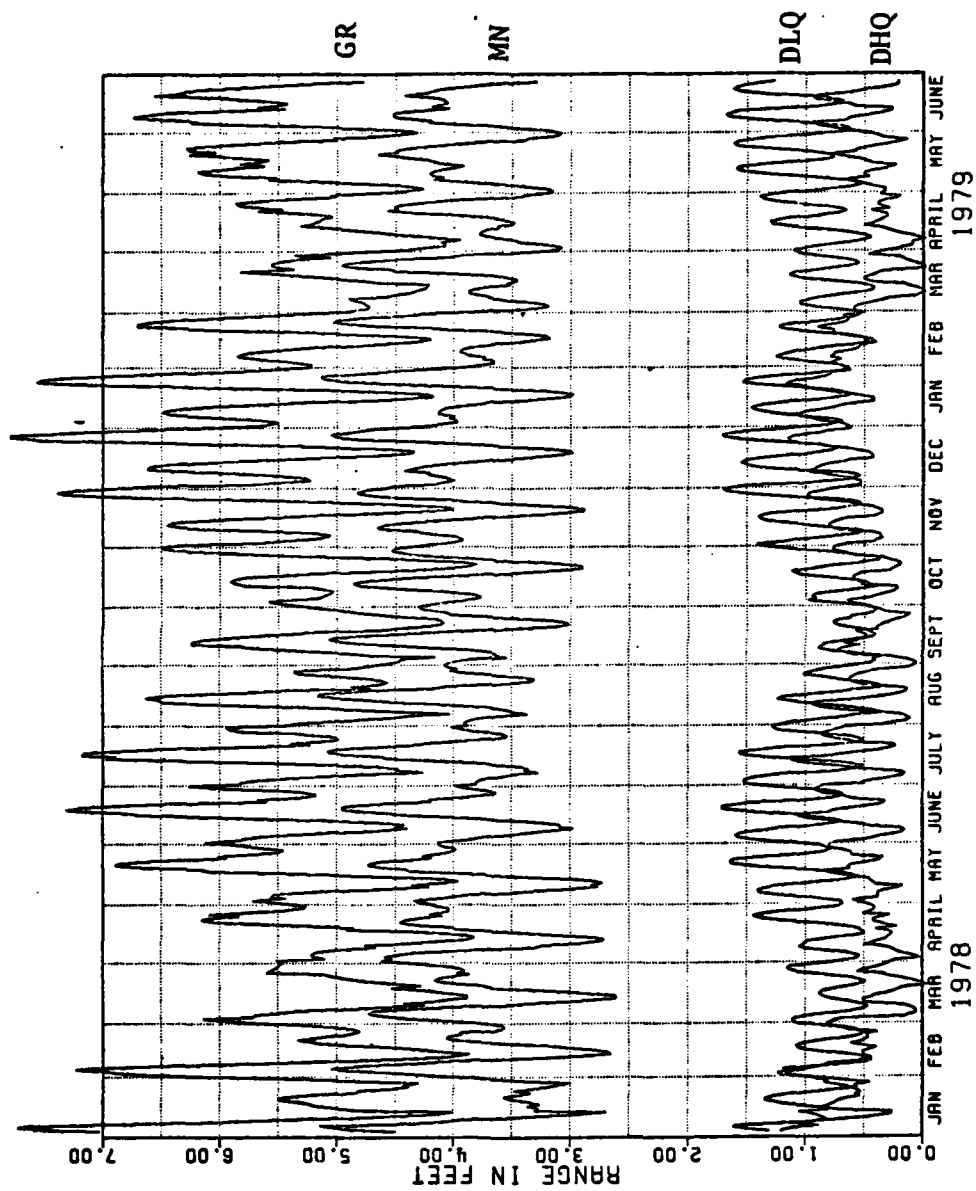
Figure 27. TIDAL RANGES AT PRESIDIO COMPUTED WITH A 7-DAY RUNNING MEAN.

97
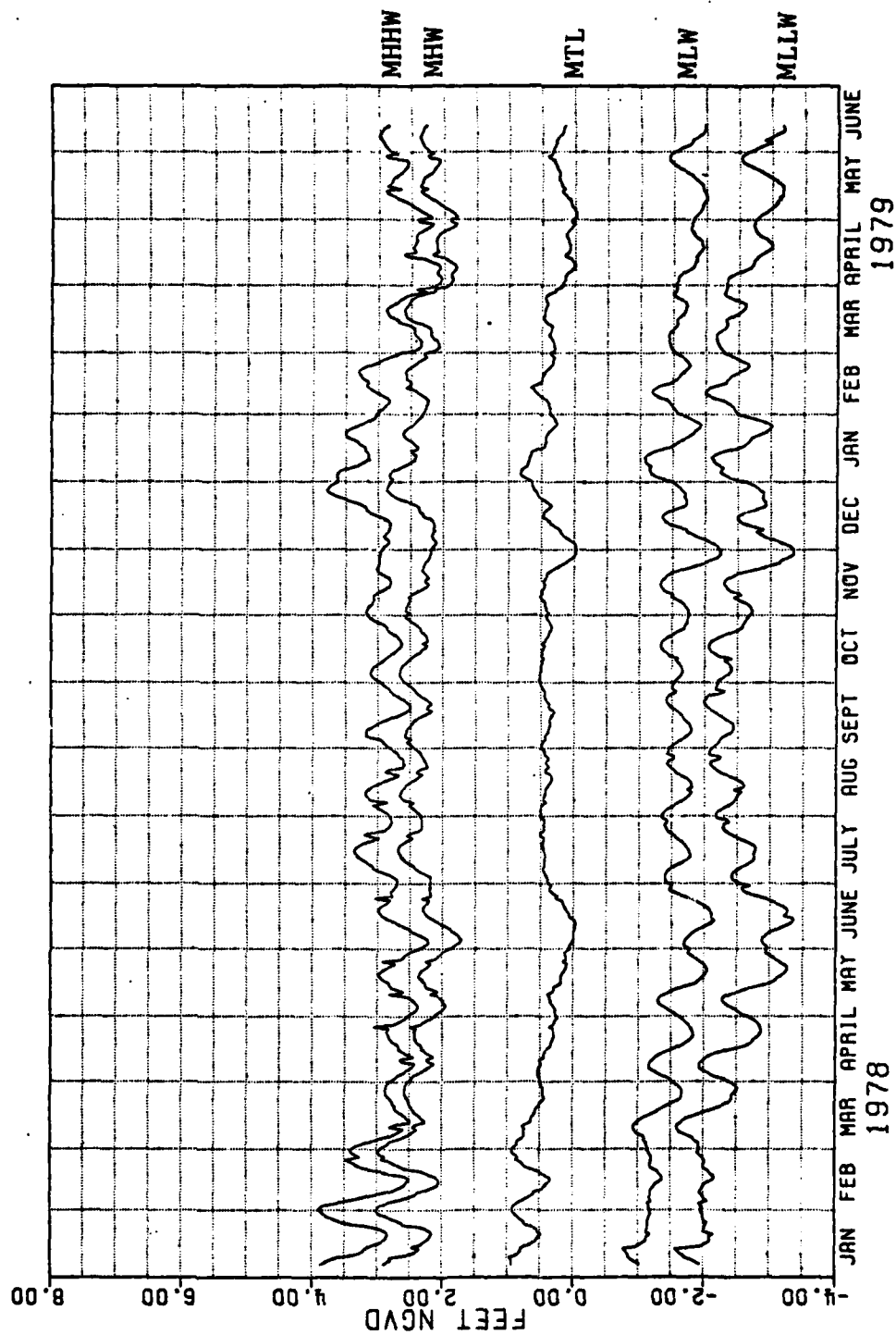
Figure 28. TIDAL DATUMS AT PRESIDIO COMPUTED WITH A 14-DAY RUNNING MEAN.
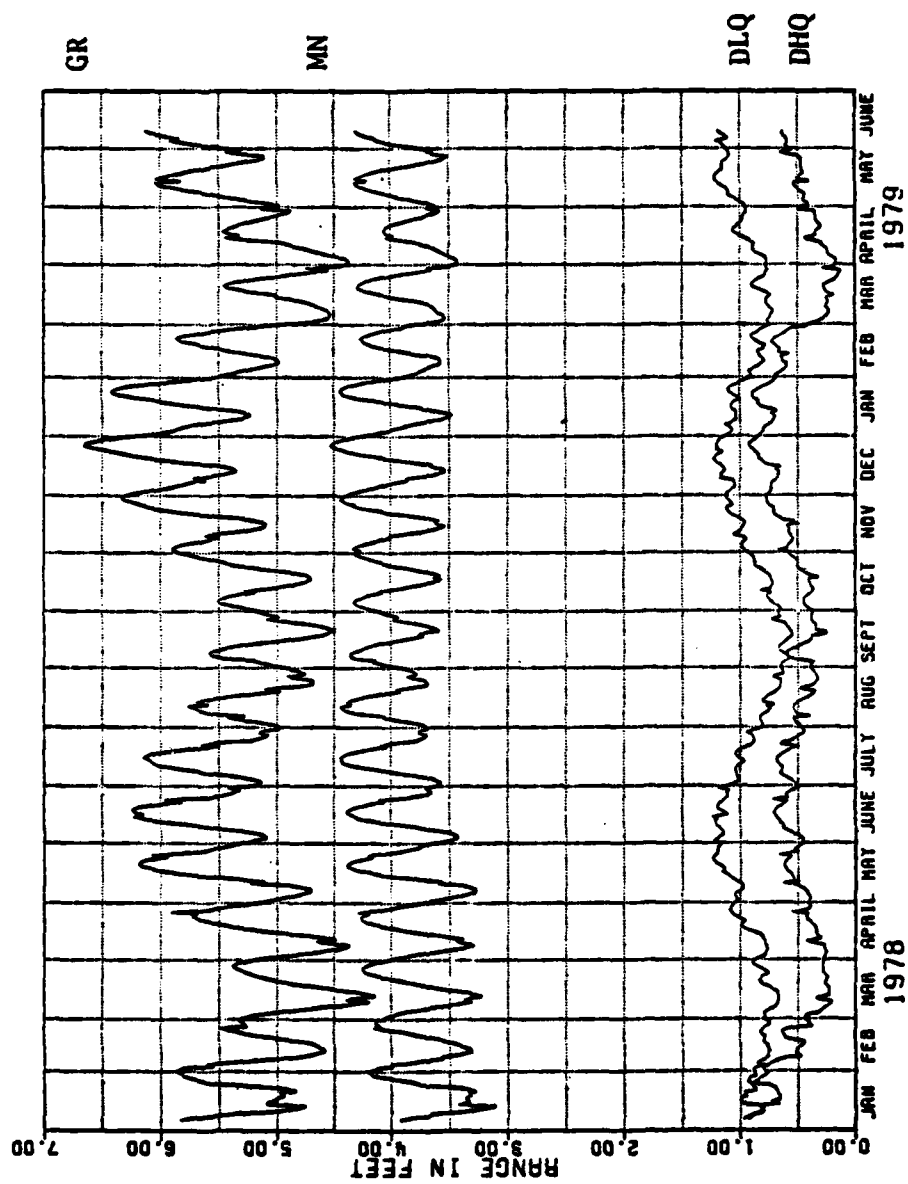
Figure 29. TIDAL RANGES AT PRESIDIO COMPUTED WITH A 14-DAY RUNNING MEAN.

99
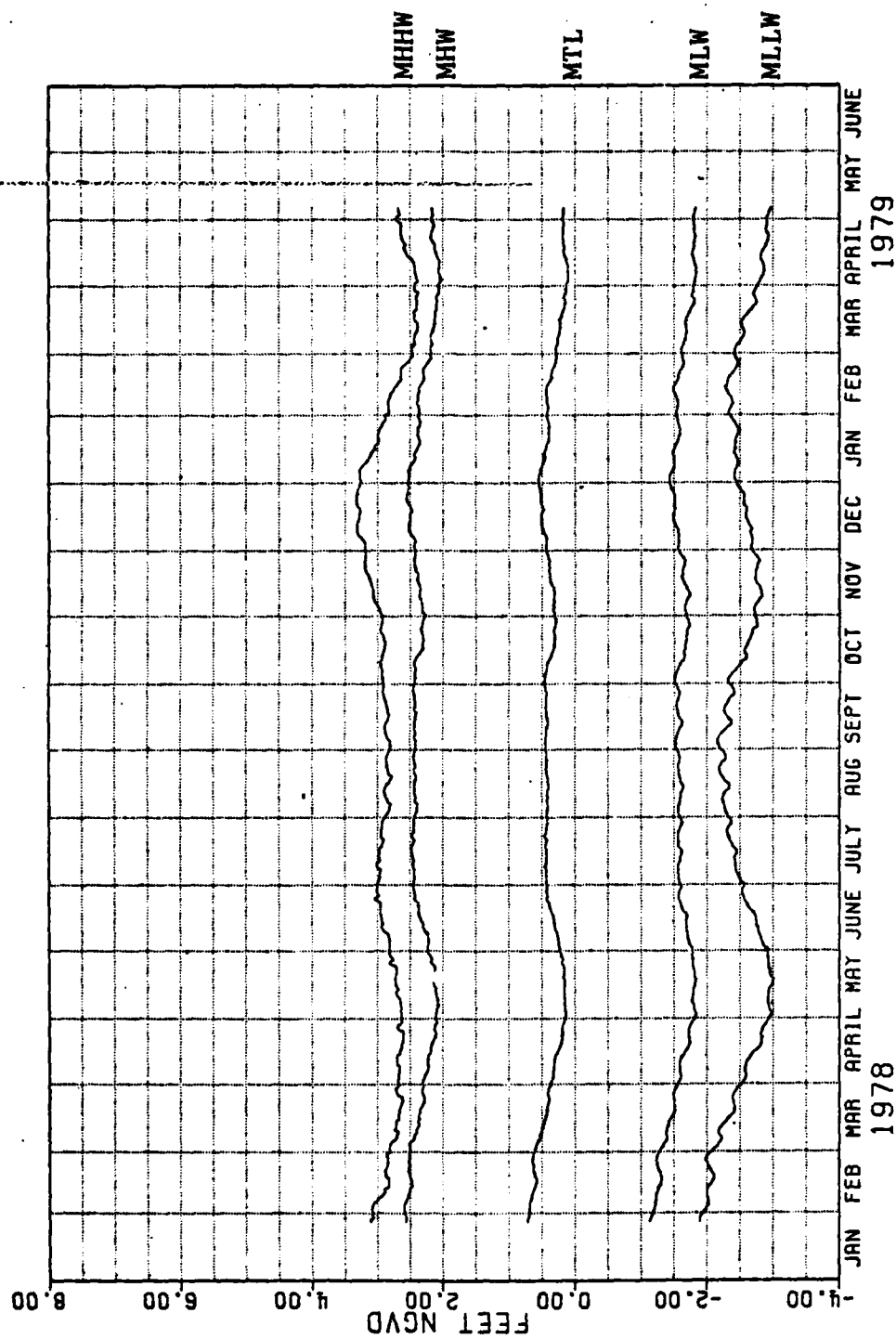
Figure 30. TIDAL DATUMS AT PRESIDIO FROM A 56-DAY RUNNING MEAN.

100
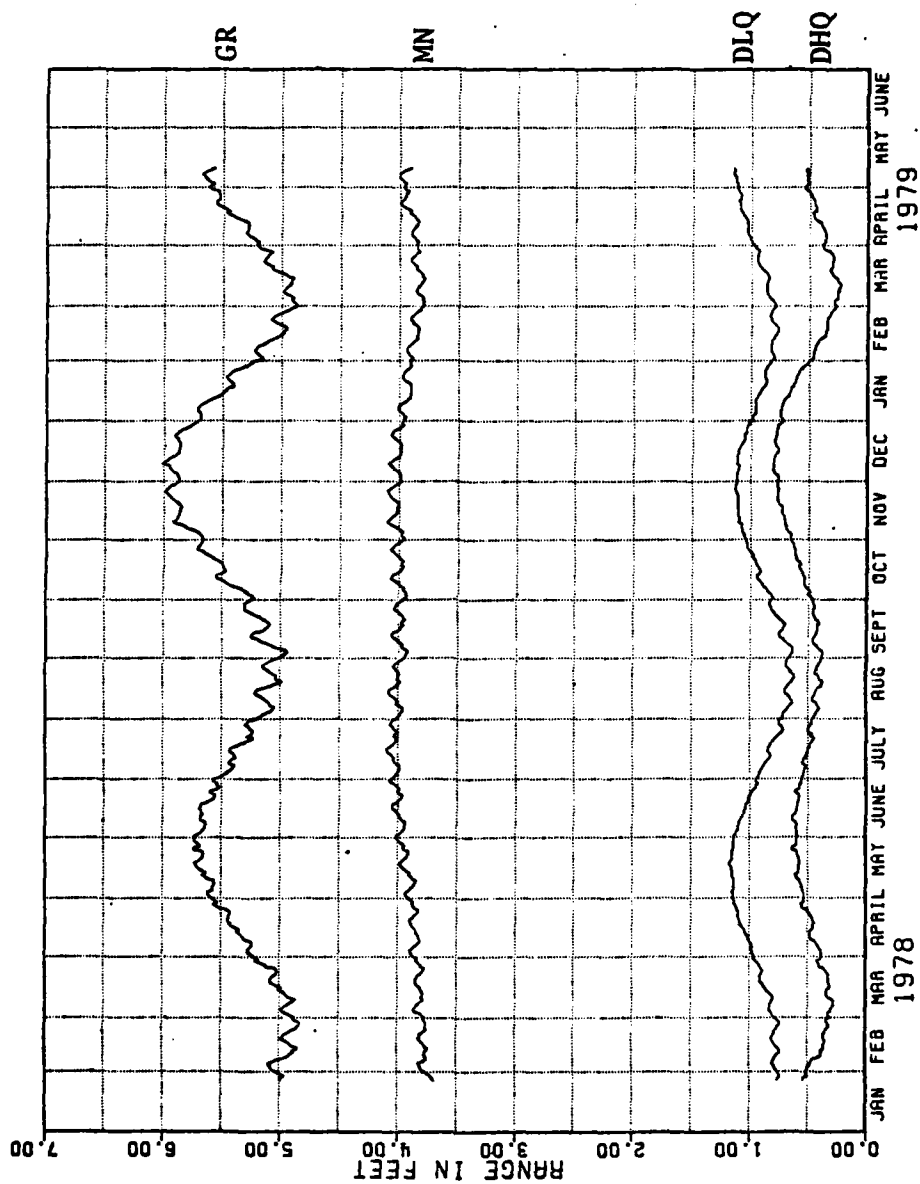
Figure 31.   TIDAL RANGES AT PRESIDIO COMPUTED WITH
A 56-DAY RUNNING MEAN.

101
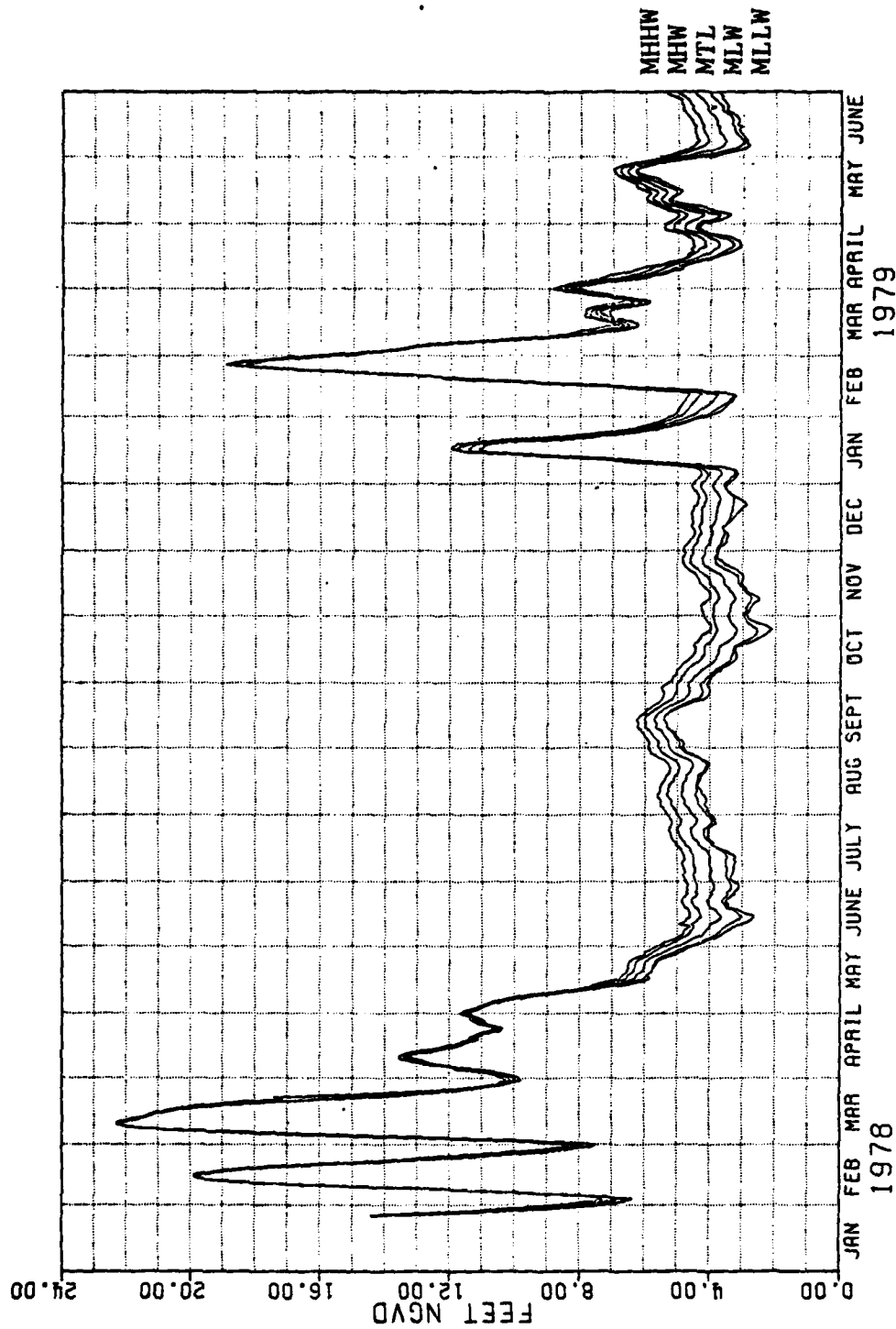
Figure 32. 19-YEAR TIDAL DATUMS AT SACRAMENTO FROM 7-DAY COMPARISONS.

102
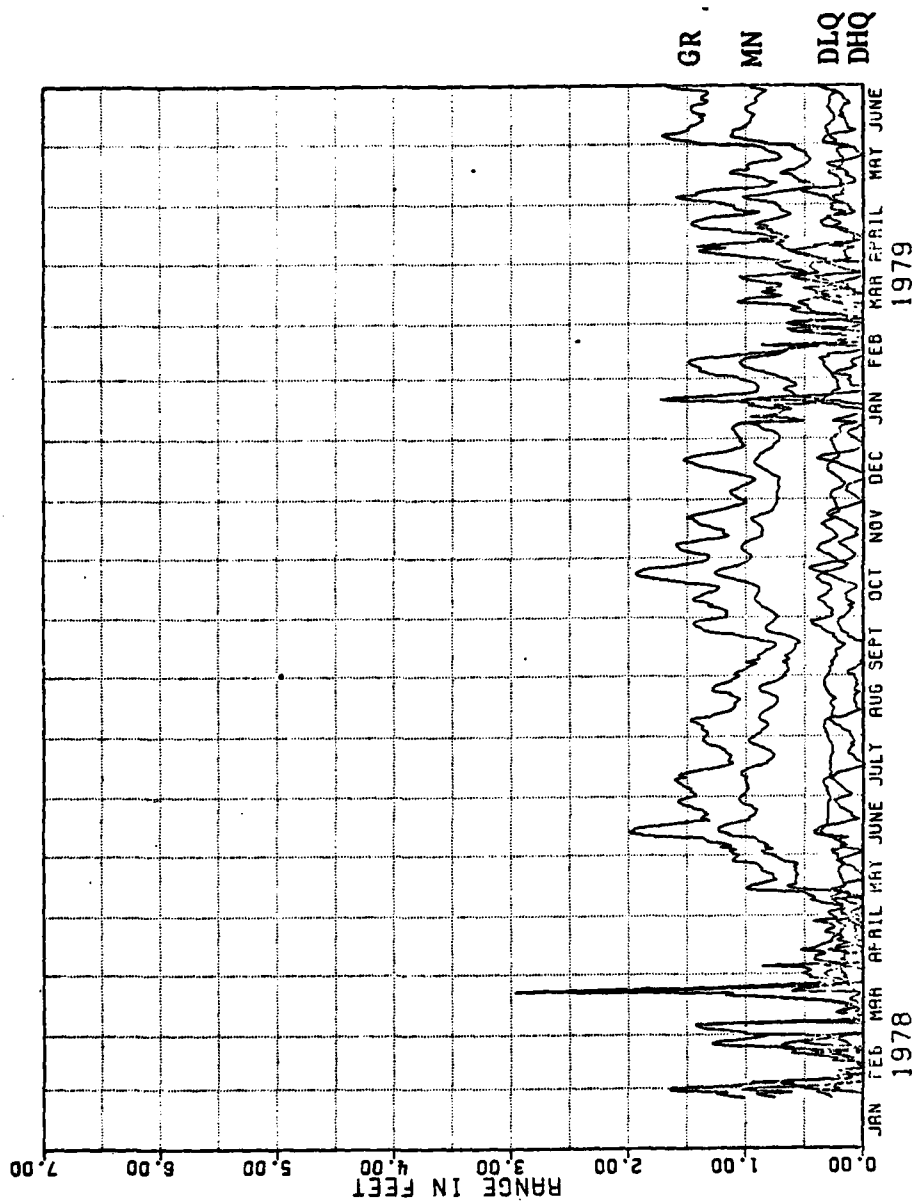
Figure 33.  19-YEAR TIDAL RANGES AT SACRAMENTO FROM 7-DAY COMPARISONS.

103
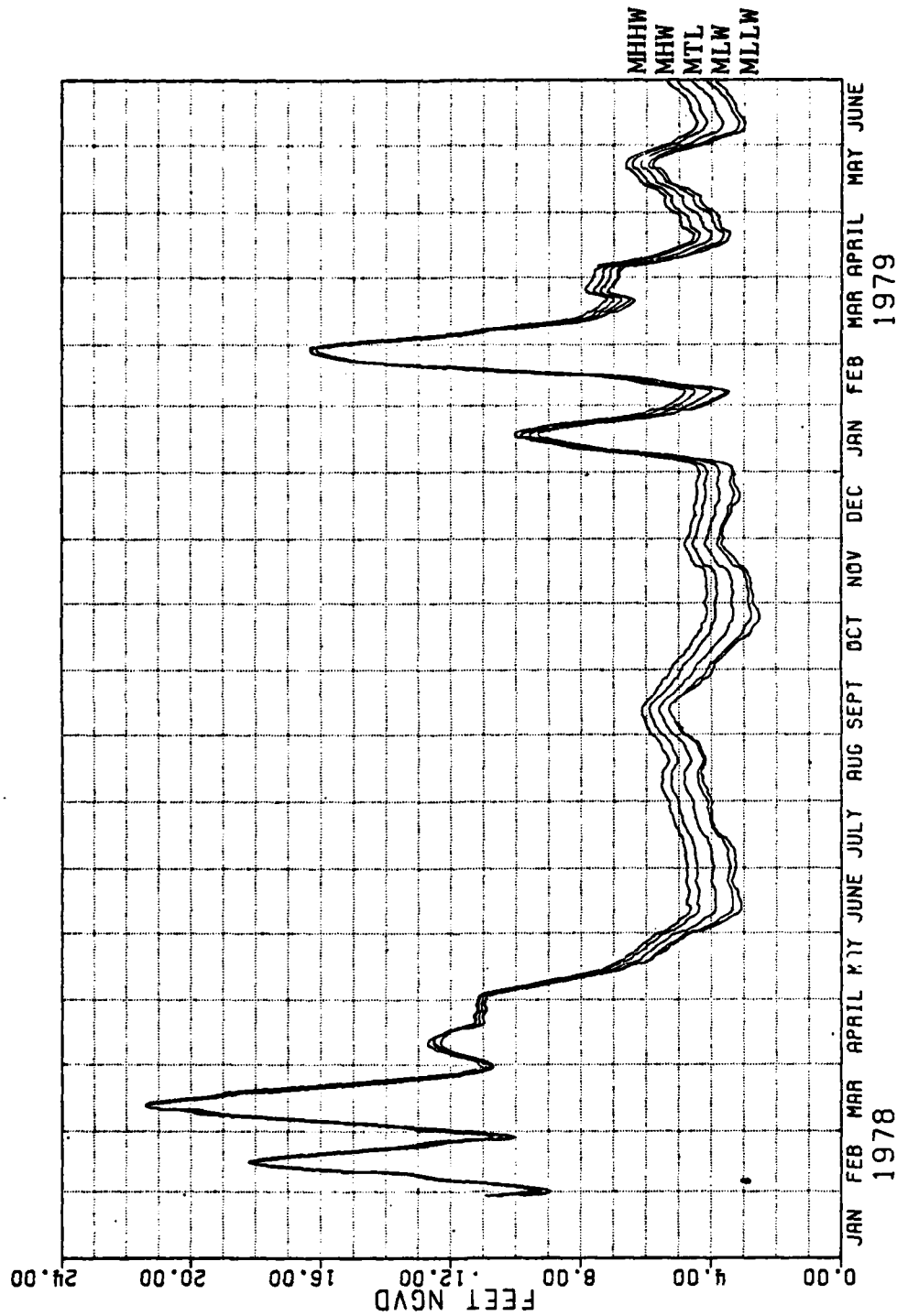
Figure 34. 19-YEAR TIDAL DATUMS AT SACRAMENTO FROM 14-DAY COMPARISONS.

104
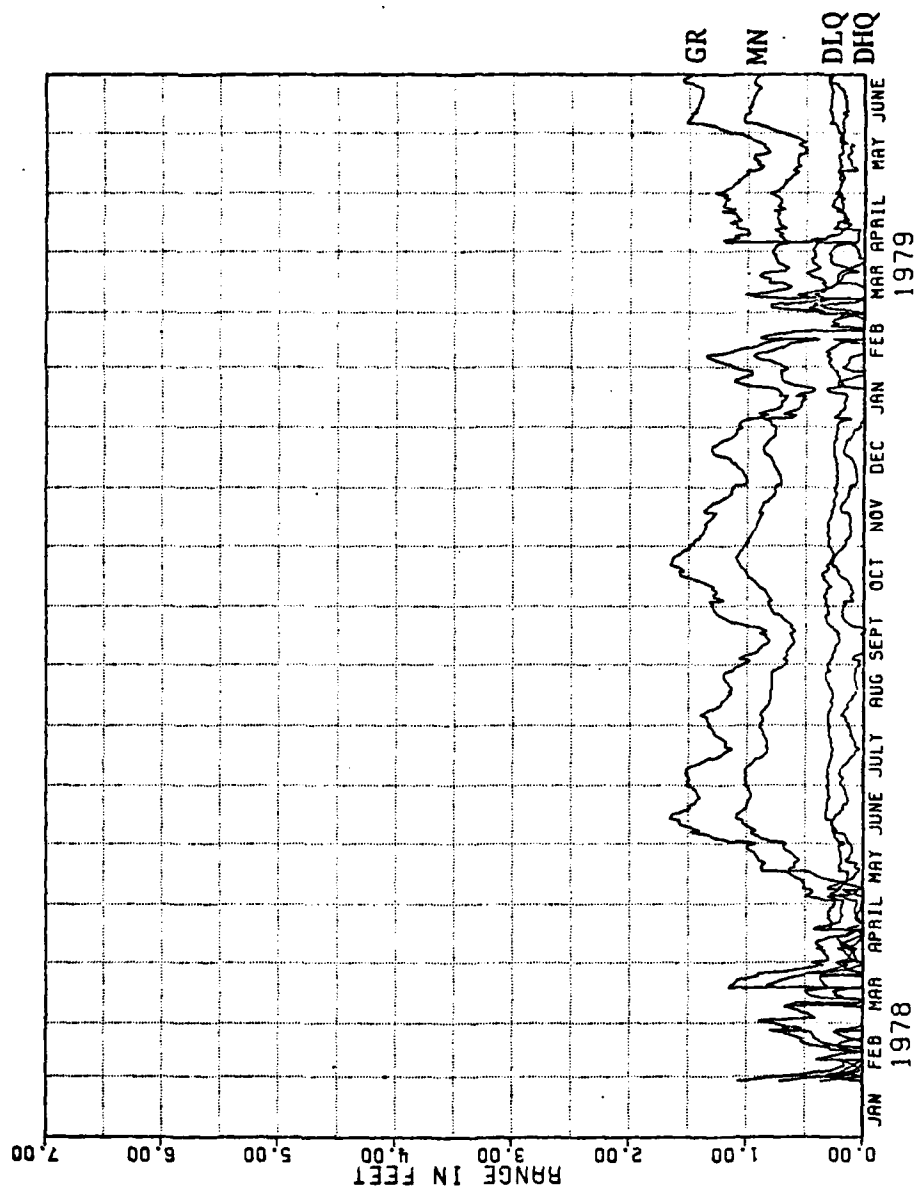
Figure 35. 19-YEAR TIDAL RANGES AT SACRAMENTO FROM 14-DAY COMPARISONS.

105
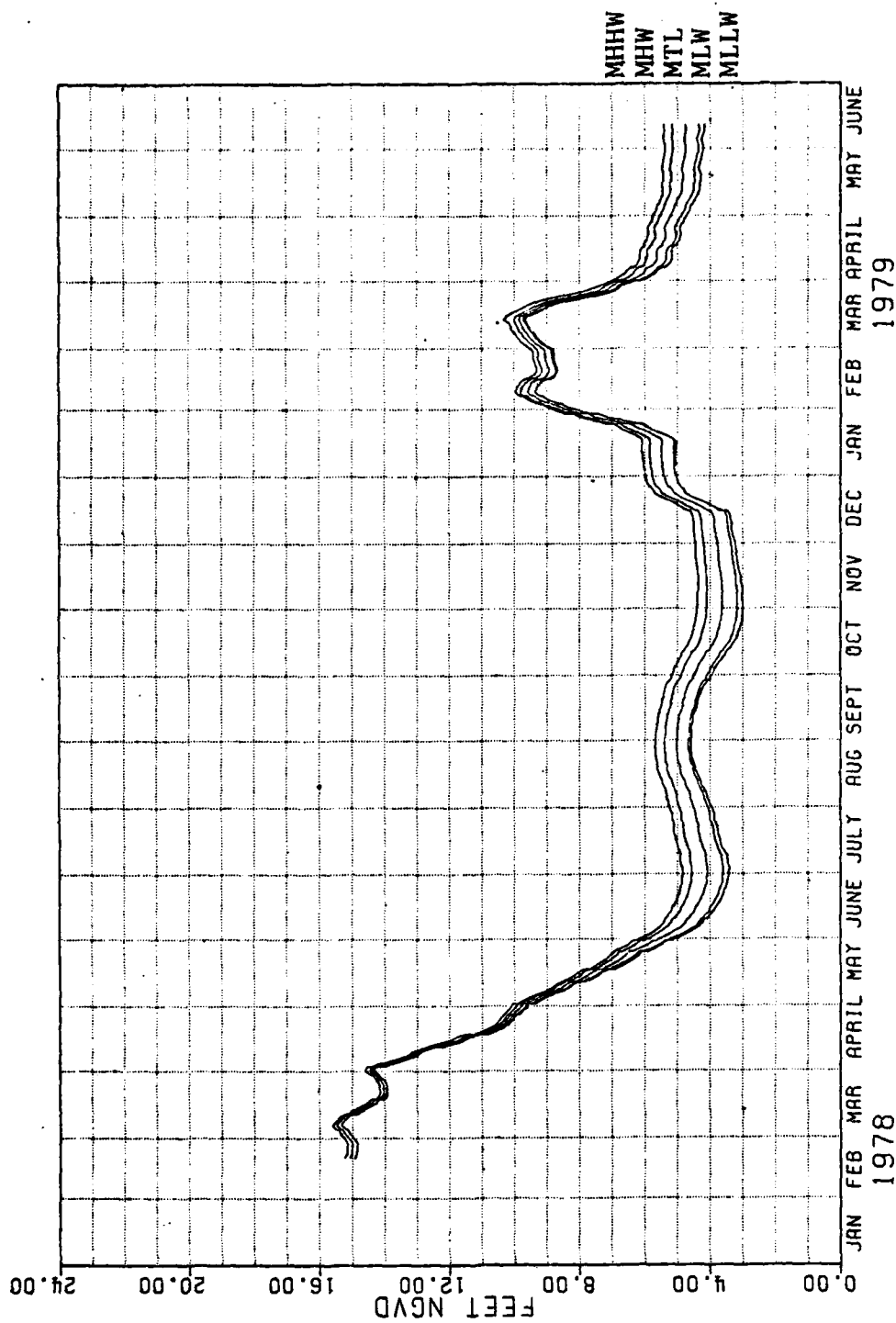
Figure 36. 19-YEAR TIDAL DATUMS AT SACRAMENTO FROM 56-DAY COMPARISONS.

106
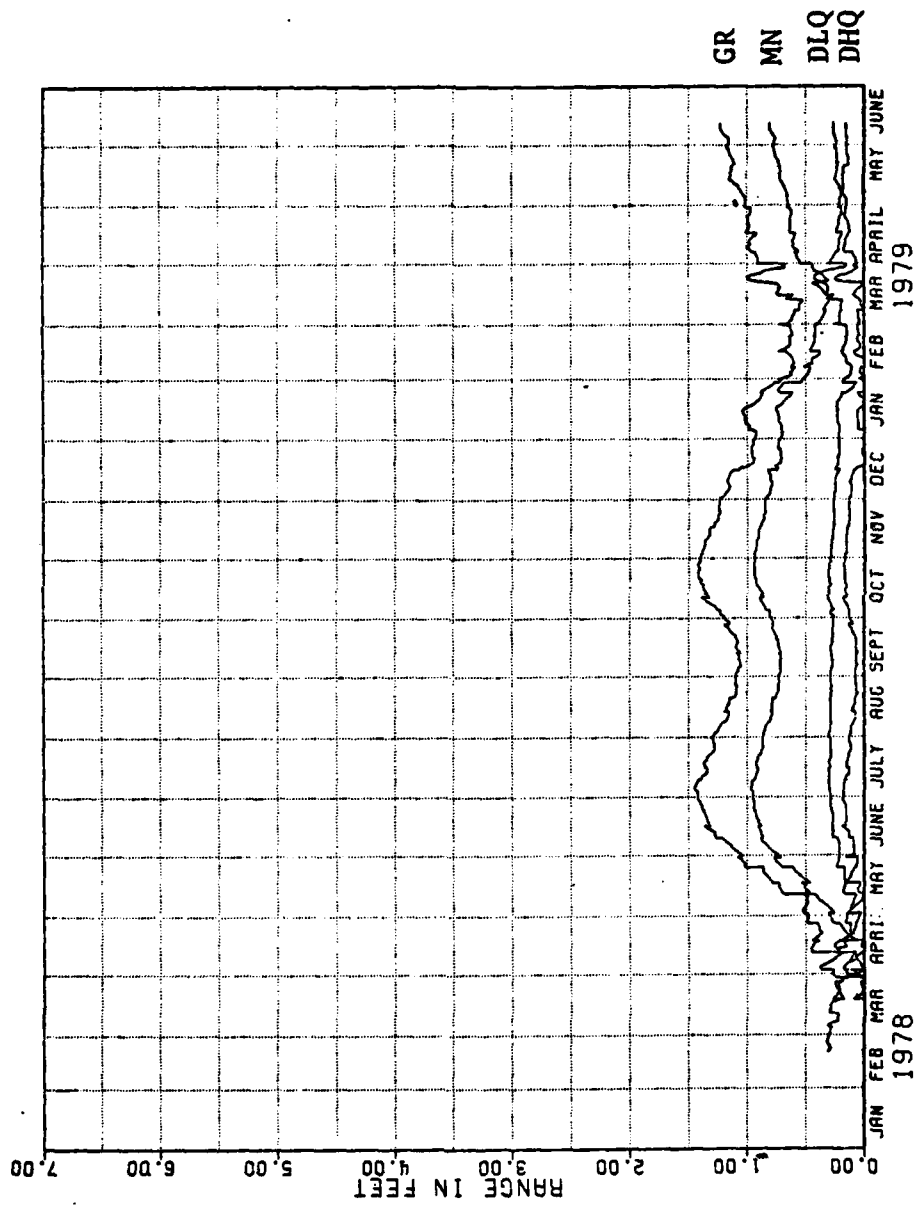
Figure 37. 19-YEAR TIDAL RANGES AT SACRAMENTO FROM 56-DAY COMPARISONS.
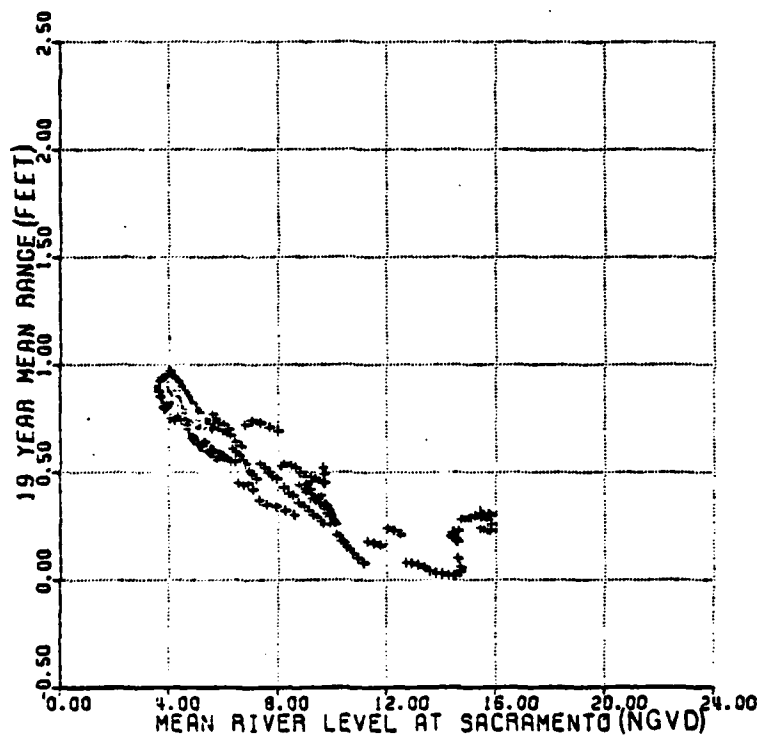
Figure 38.   19-YEAR MEAN RANGE AT
SACRAMENTO RELATIVE TO
MEAN RIVER LEVEL FROM
56-DAY COMPARISONS.
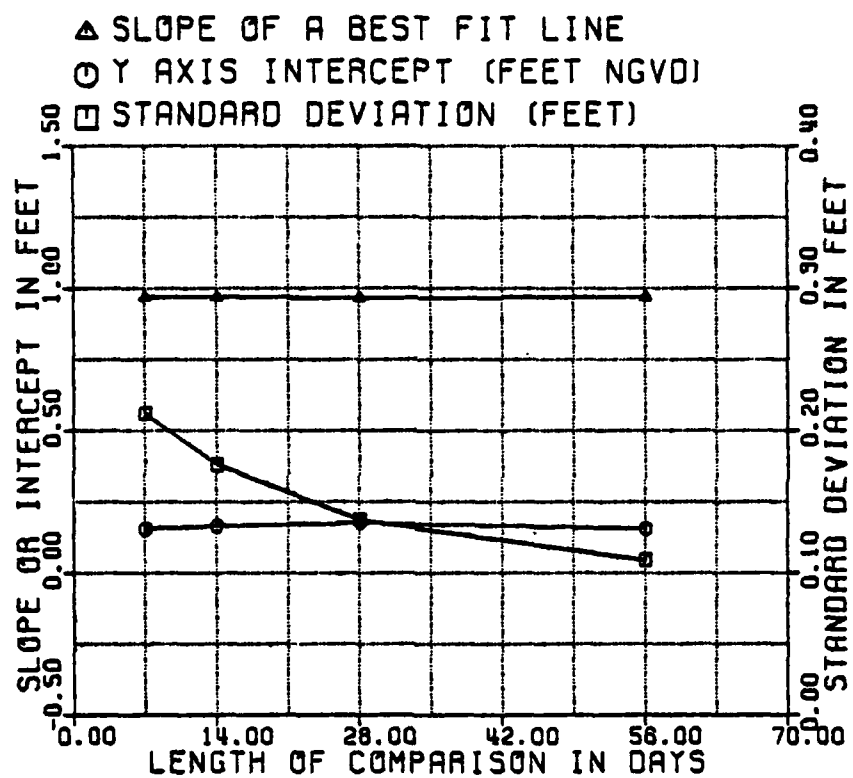
Figure 39. VARIABILITY OF 19-YEAR MEAN TIDE LEVELS RELATIVE
TO MEAN RIVER LEVELS WITH COMPARISON INTERVAL AT
SACRAMENTO.
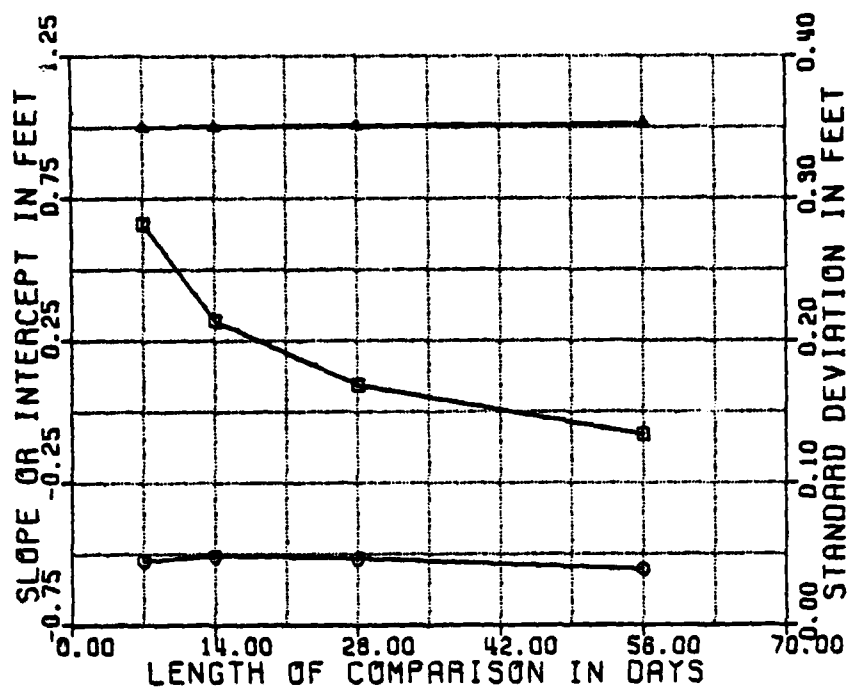
Figure 40.  VARIABILITY OF 19-YEAR MEAN LOWER LOW WATERS RELATIVE TO MEAN RIVER LEVELS WITH COMPARISON INTERVAL AT SACRAMENTO.

△ SLOPE OF A BEST FIT LINE
◉ Y AXIS INTERCEPT (FEET NGVD)
▢ STANDARD DEVIATION (FEET)
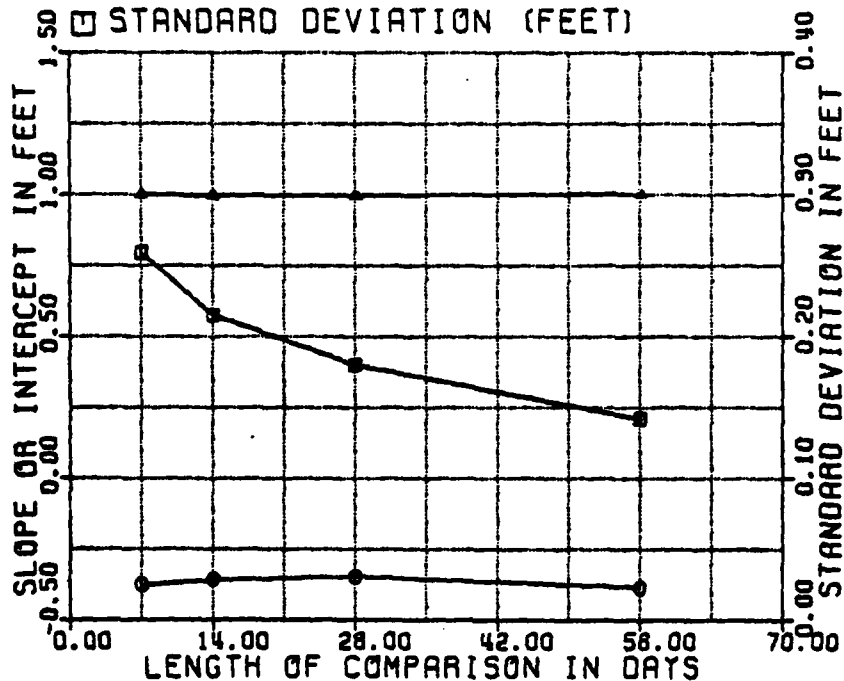


Figure 41.  VARIABILITY OF 19-YEAR MEAN LOW WATERS RELATIVE TO MEAN RIVER LEVELS WITH COMPARISON INTERVAL AT SACRAMENTO.

110
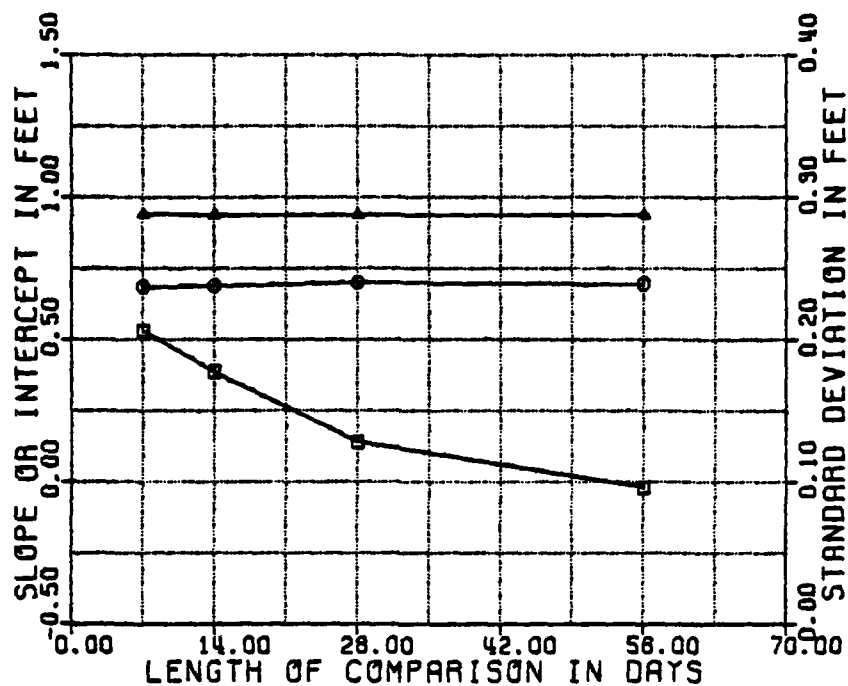
Figure 42. VARIABILITY OF 19-YEAR MEAN HIGH WATERS RELATIVE TO MEAN RIVER LEVELS WITH COMPARISON INTERVAL AT SACRAMENTO.

△ SLOPE OF A BEST FIT LINE

⊙ Y AXIS INTERCEPT (FEET NGVD)

□ STANDARD DEVIATION (FEET)
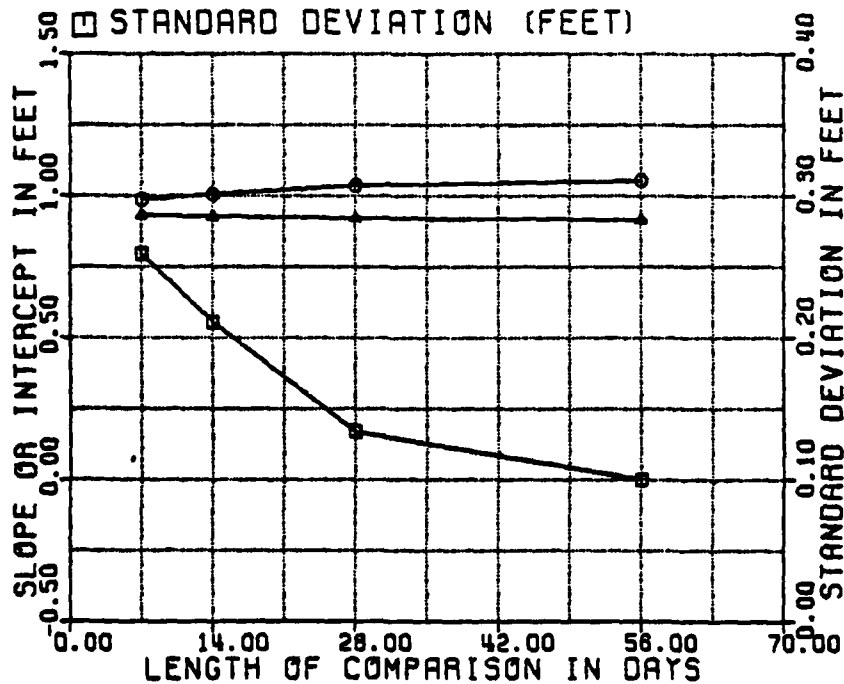


Figure 43. VARIABILITY OF 19-YEAR MEAN HIGHER HIGH WATERS RELATIVE TO MEAN RIVER LEVELS WITH COMPARISON INTERVAL AT SACRAMENTO.

111
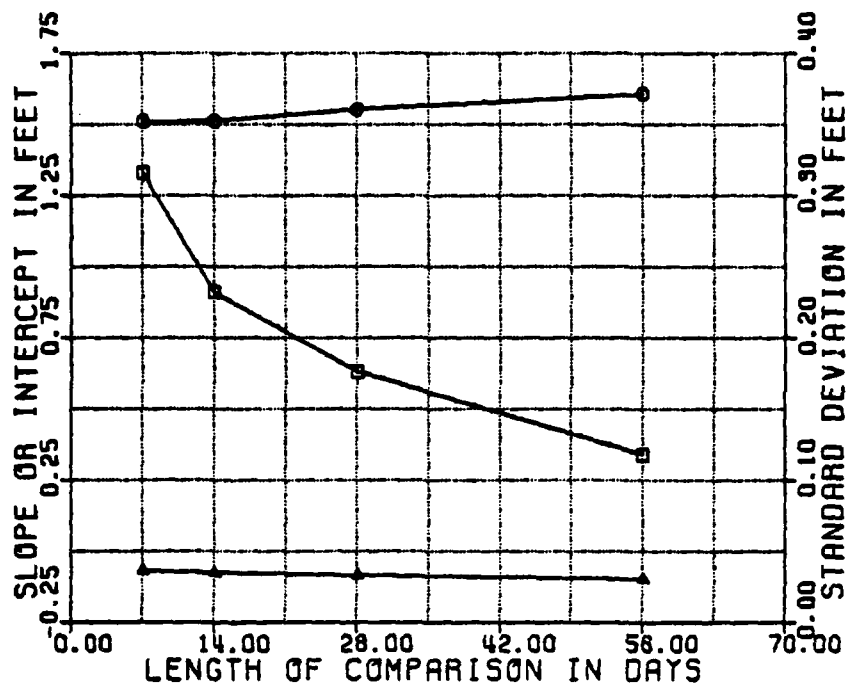
Figure 44.   VARIABILITY OF 19-YEAR GREATER RANGES RELATIVE TO
             MEAN RIVER LEVELS WITH COMPARISON INTERVALS AT
             SACRAMENTO.

             △ SLOPE OF A BEST FIT LINE

             ⊙ Y AXIS INTERCEPT (FEET NGVD)

             ▢ STANDARD DEVIATION (FEET)
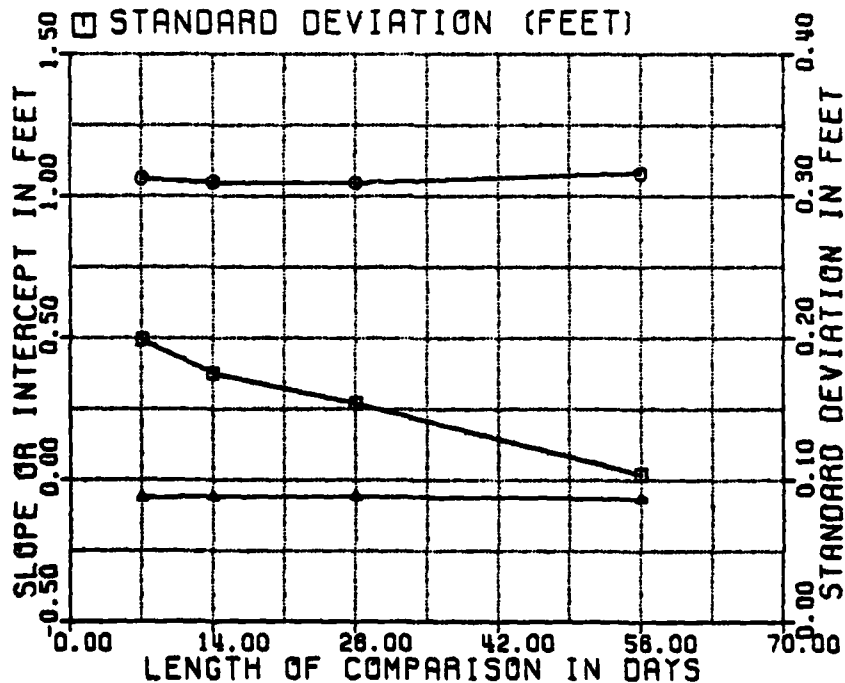


Figure 45.   VARIABILITY OF 19-YEAR MEAN RANGES RELATIVE TO MEAN
             RIVER LEVELS WITH COMPARISON INTERVAL AT SACRAMENTO.
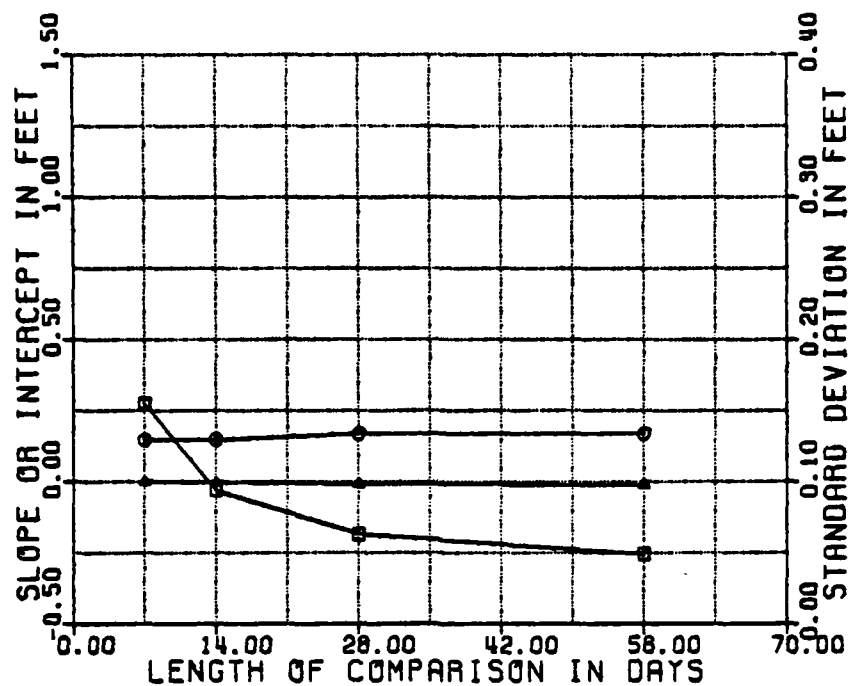
Figure 46. VARIABILITY OF 19-YEAR DIURNAL LOW INEQUALITIES
RELATIVE TO MEAN RIVER LEVELS WITH COMPARISON
INTERVAL AT SACRAMENTO.

△ SLOPE OF A BEST FIT LINE
⊙ Y AXIS INTERCEPT (FEET NGVD)
▢ STANDARD DEVIATION (FEET)
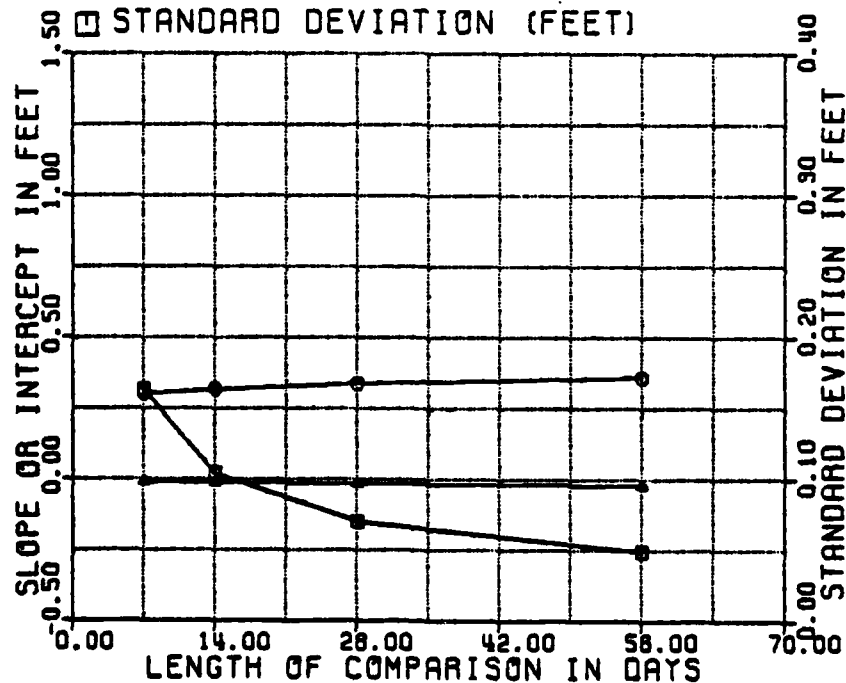


Figure 47. VARIABILITY OF 19-YEAR DIURNAL HIGH INEQUALITIES
RELATIVE TO MEAN RIVER LEVELS WITH COMPARISON
INTERVAL AT SACRAMENTO.

113
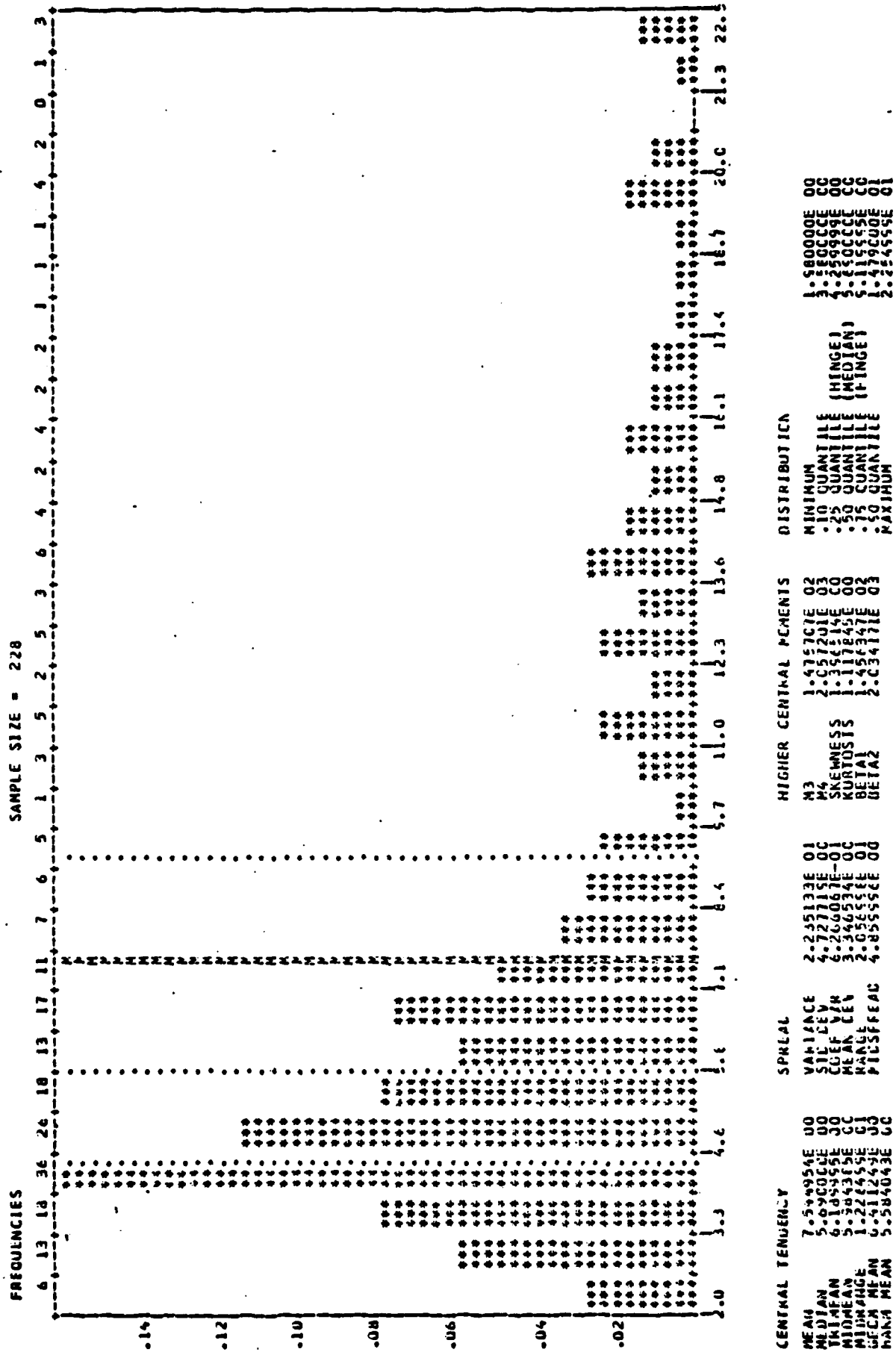
Figure 48. HISTOGRAM OF MONTHLY MEAN RIVER LEVELS (NGVD) AT SACRAMENTO FOR THE EPOCH 1960-1978.

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# APPENDIX A. GRAPHS

| Time Series | POINT ORIENT | BENICIA | MALLARD ISLAND | COLLINSVILLE | THREE MILE SLOUGH | WALNUT GROVE | SACRAMENTO | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | 7-DAY COMPARISON | 14-DAY COMPARISON | 28-DAY COMPARISON | 56-DAY COMPARISON |
| Datums | 0-1 | B-1 | M-1 | C-1 | T-1 | W-1 | 32 | 34 | 11 | 36 |
| Ranges | 0-2 | B-2 | M-2 | C-2 | T-2 | W-2 | 33 | 35 | 12 | 37 |
| | | | | | | | | | | |
| Scatter Plots | | | | | | | | | | |
| MTL | 0-3 | B-3 | M-3 | | T-3 | W-3 | Q-3 | R-3 | S-3 | V-3 |
| MLLW | 0-4 | B-4 | M-4 | | T-4 | W-4 | Q-4 | R-4 | S-4 | V-4 |
| MLW | 0-5 | B-5 | M-5 | | T-5 | W-5 | Q-5 | R-5 | S-5 | V-5 |
| MHW | 0-6 | B-6 | M-6 | | T-6 | W-6 | Q-6 | R-6 | S-6 | V-6 |
| MHHW | 0-7 | B-7 | M-7 | | T-7 | W-7 | Q-7 | R-7 | S-7 | V-7 |
| GR | 0-8 | B-8 | M-8 | | T-8 | W-8 | Q-8 | R-8 | S-8 | V-8 |
| MN | 0-9 | B-9 | M-9 | | T-9 | W-9 | Q-9 | R-9 | S-9 | V-9 |
| DLQ | 0-10 | B-10 | M-10 | | T-10 | W-10 | Q-10 | R-10 | S-10 | V-10 |
| DHQ | 0-11 | B-11 | M-11 | | T-11 | W-11 | Q-11 | R-11 | S-11 | V-11 |

All graphs are computed from 28-day comparisons, except as otherwise indicated. All scatter plots are relative to NGVD.
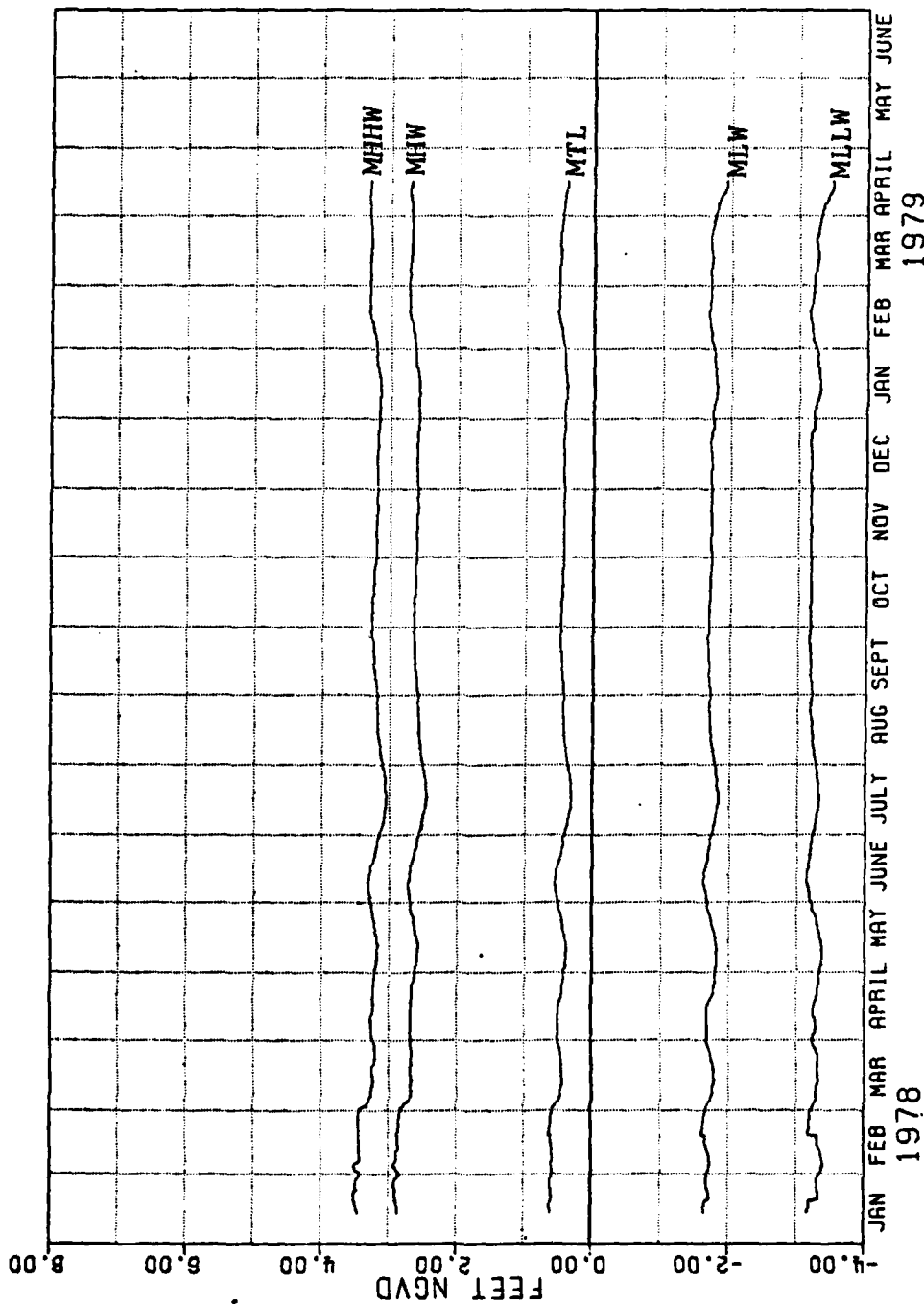
Graph 0-1. 19-YEAR TIDAL DATUMS AT POINT ORIENT.

116
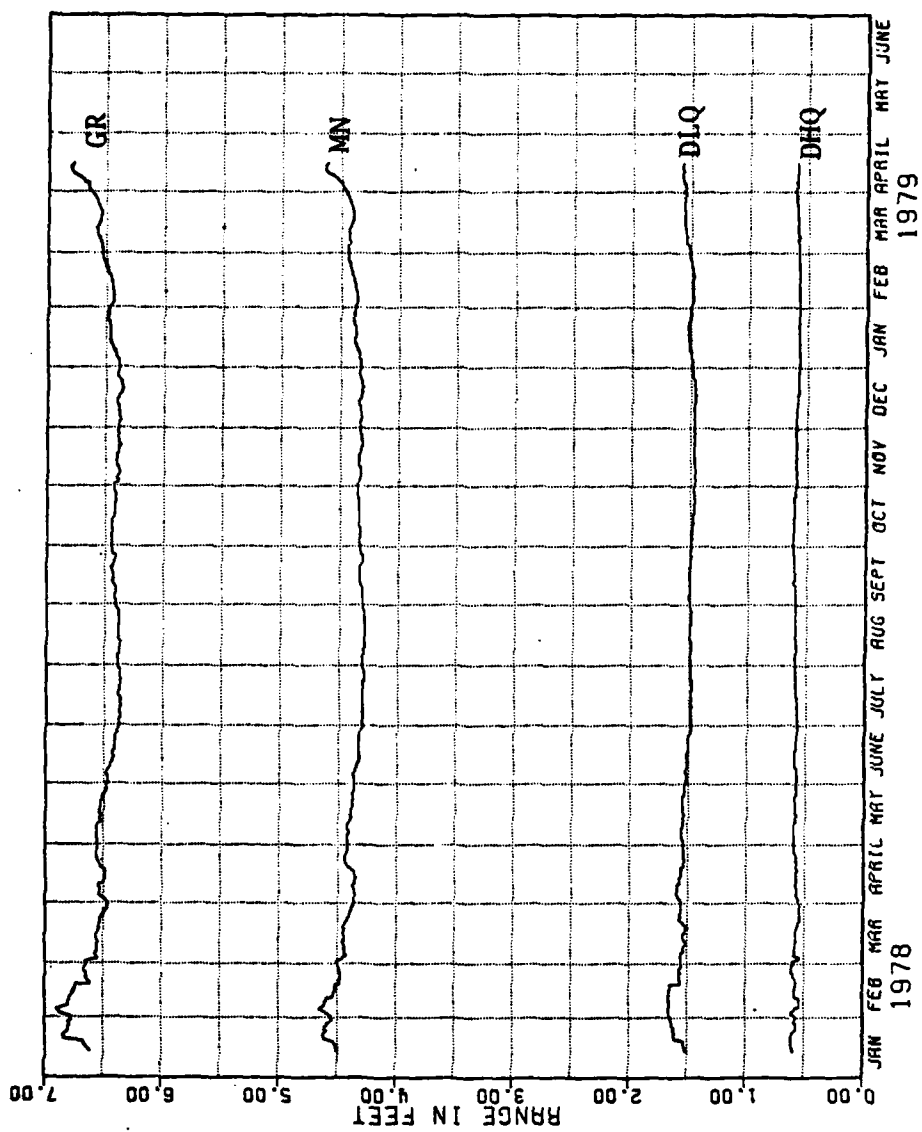
Graph 0-2. 19-YEAR TIDAL RANGES AT POINT ORIENT.

117
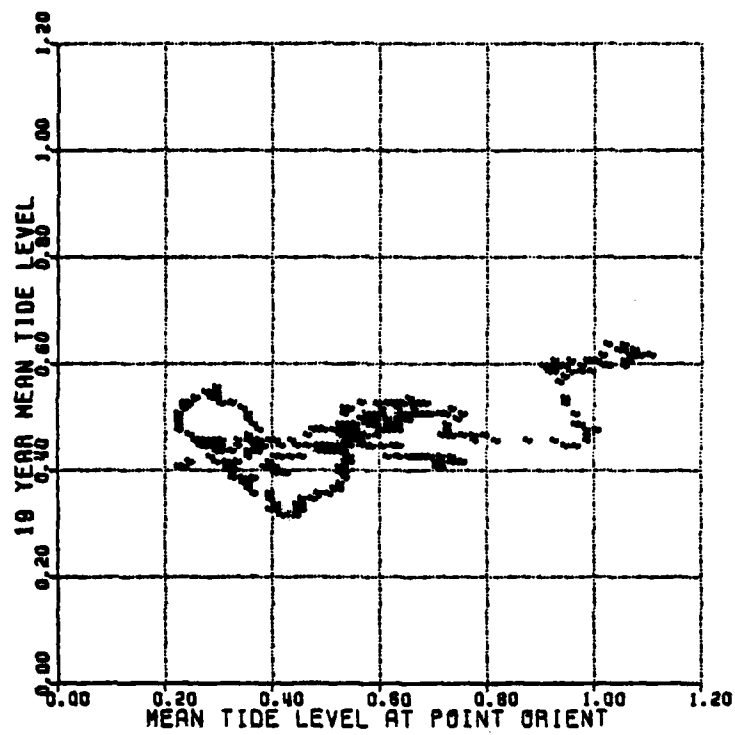
Graph 0-3

Graph 0-4



Graph 0-5

119

Graph 0-6



Graph 0-7

120

Graph 0-8



Graph 0-9

121
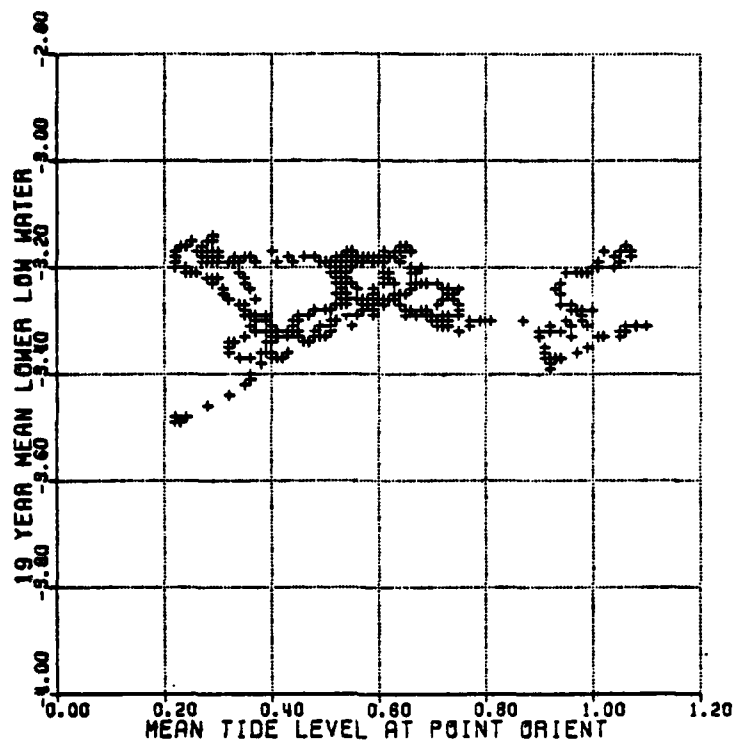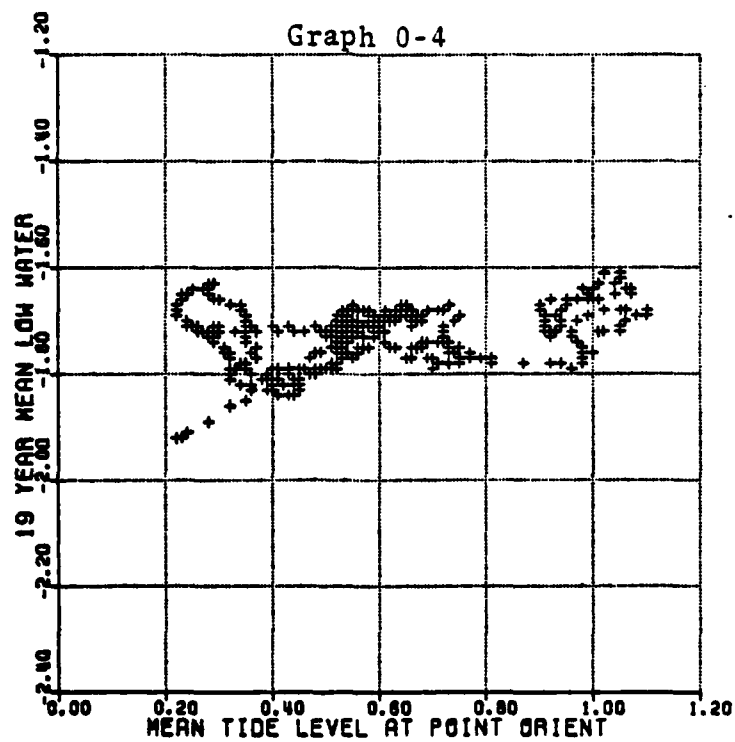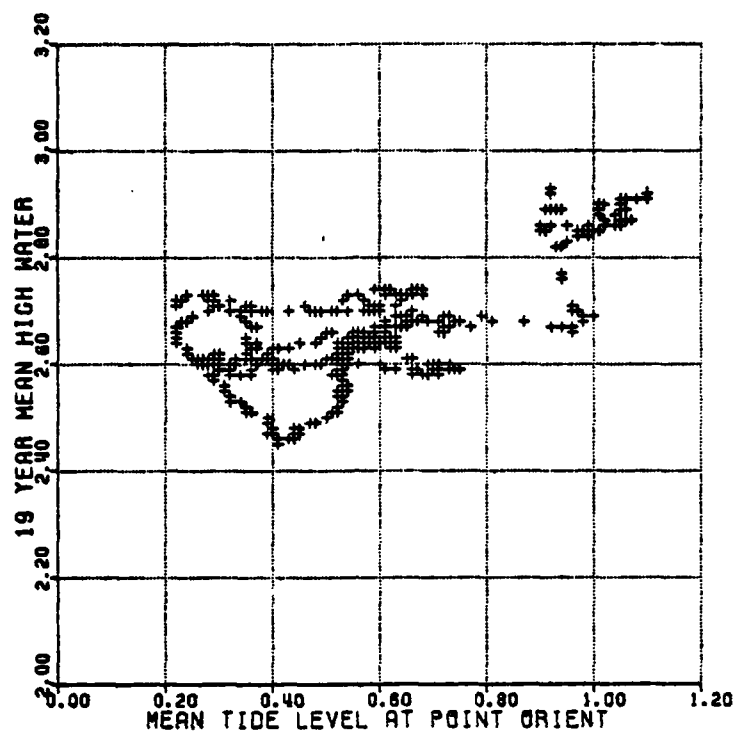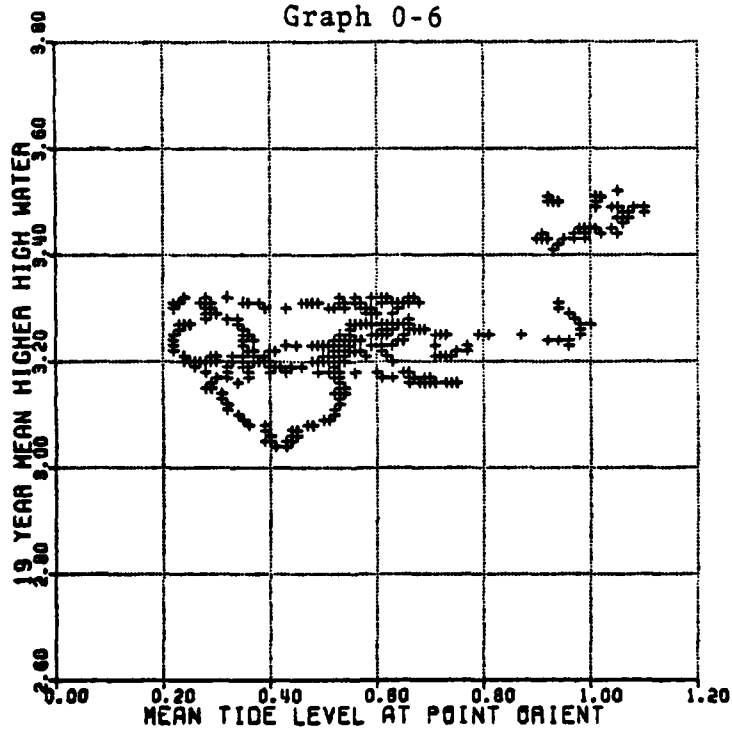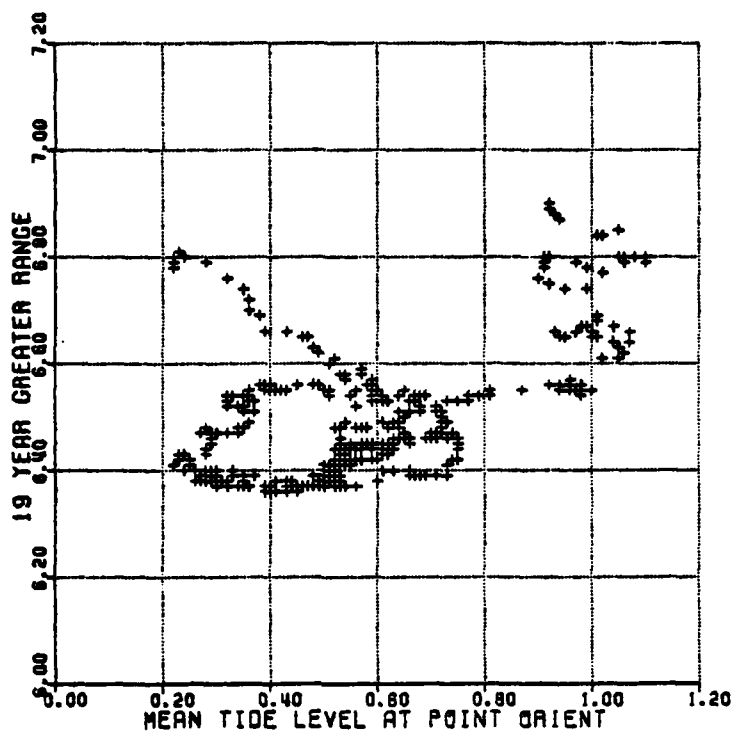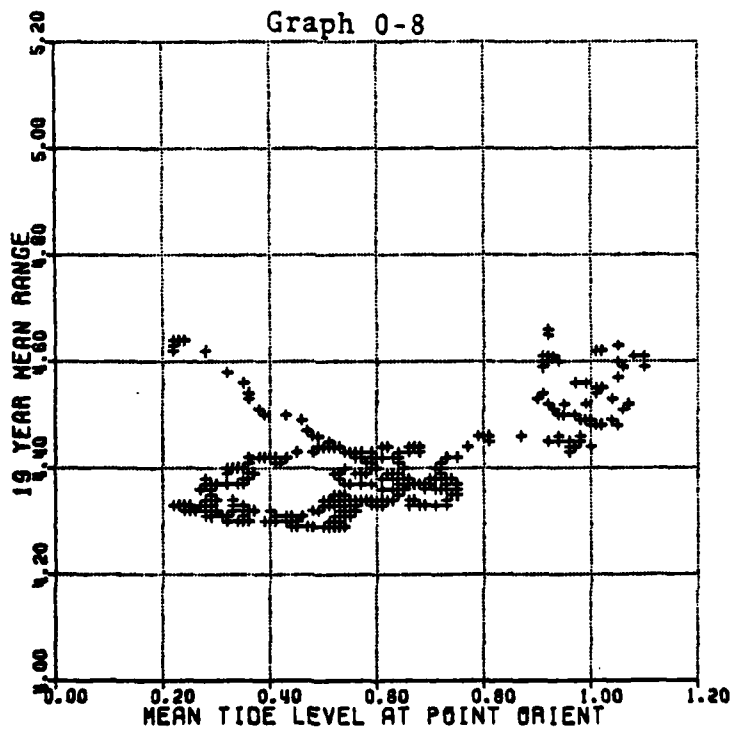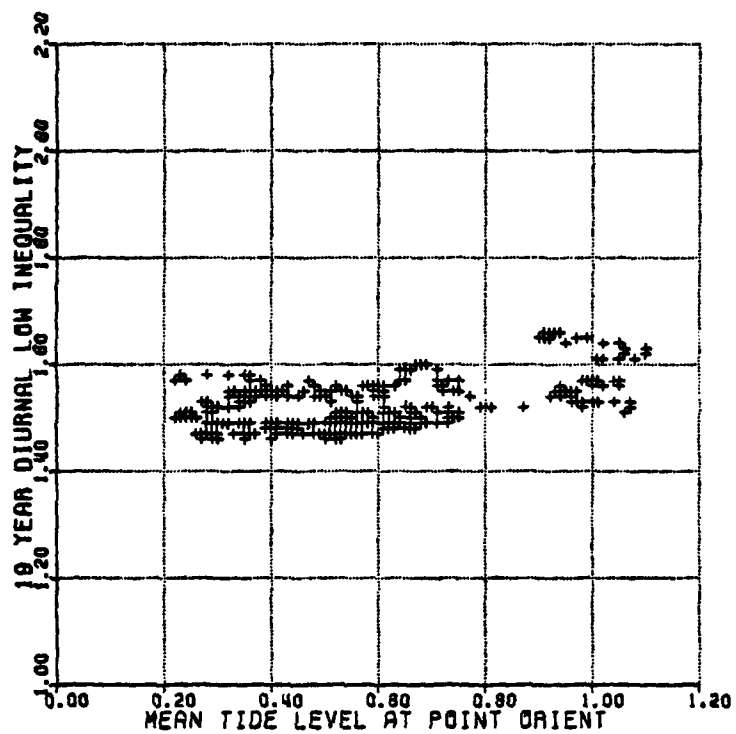
Graph 0-10



Graph 0-11

122
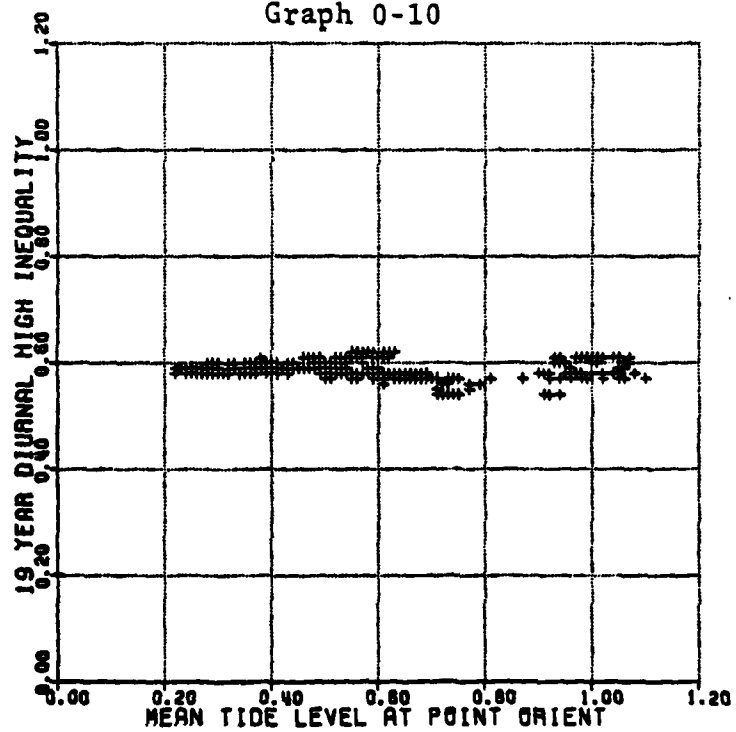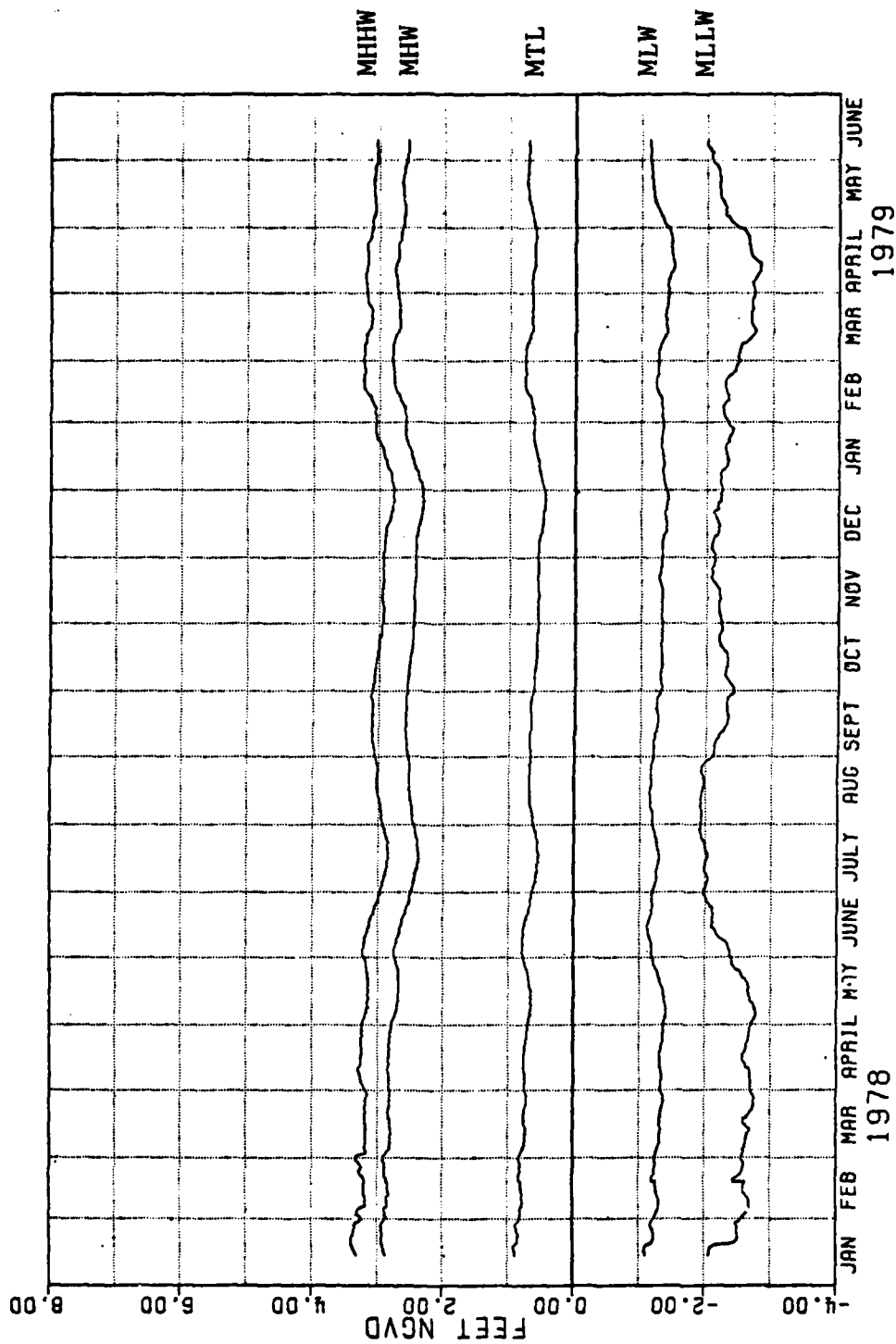
Graph B-1. 19-YEAR TIDAL DATUMS AT BENICIA.

123
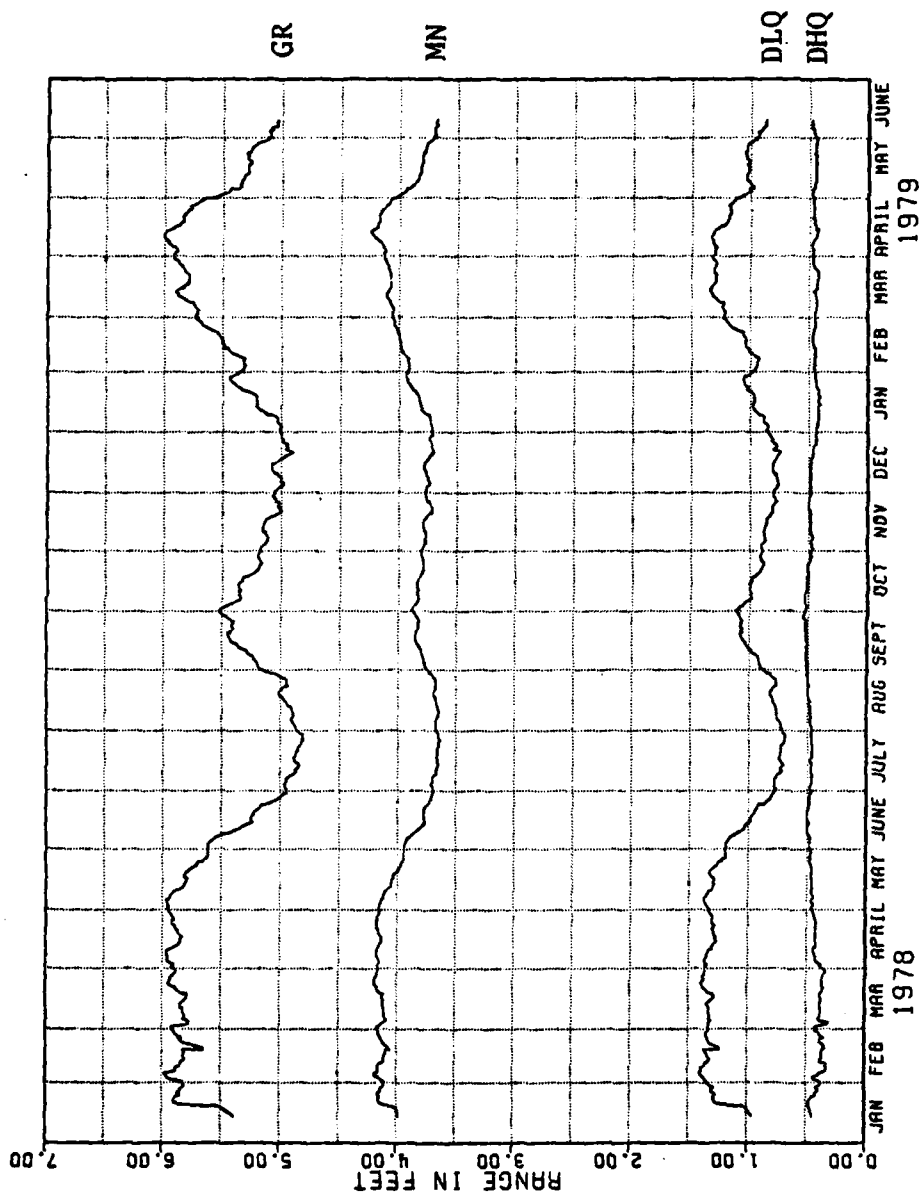
Graph B-2. 19-YEAR TIDAL RANGES AT BENICIA.

124

Graph B-3

125

Graph B-4



Graph B-5

126

Graph B-6



Graph B-7

127

Graph B-8



Graph B-9

128
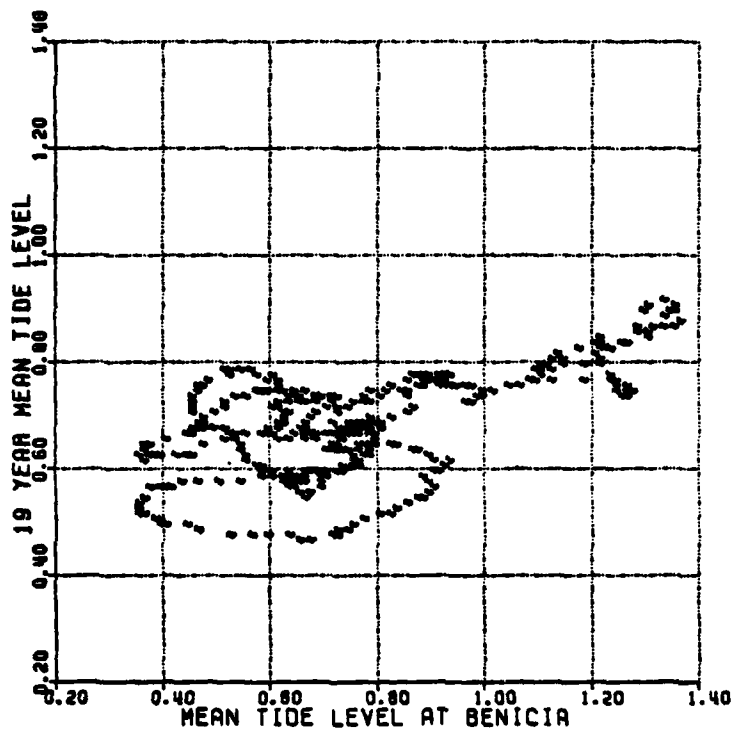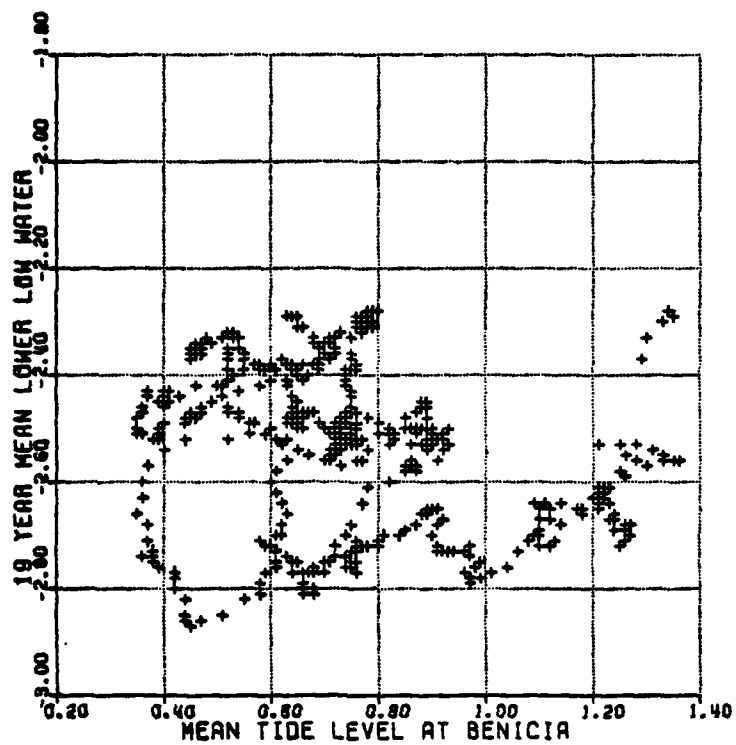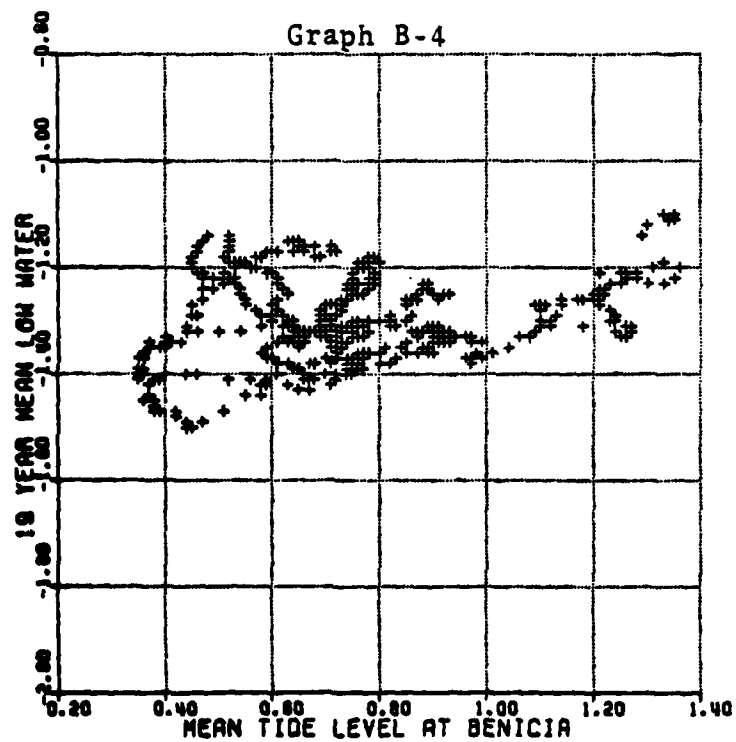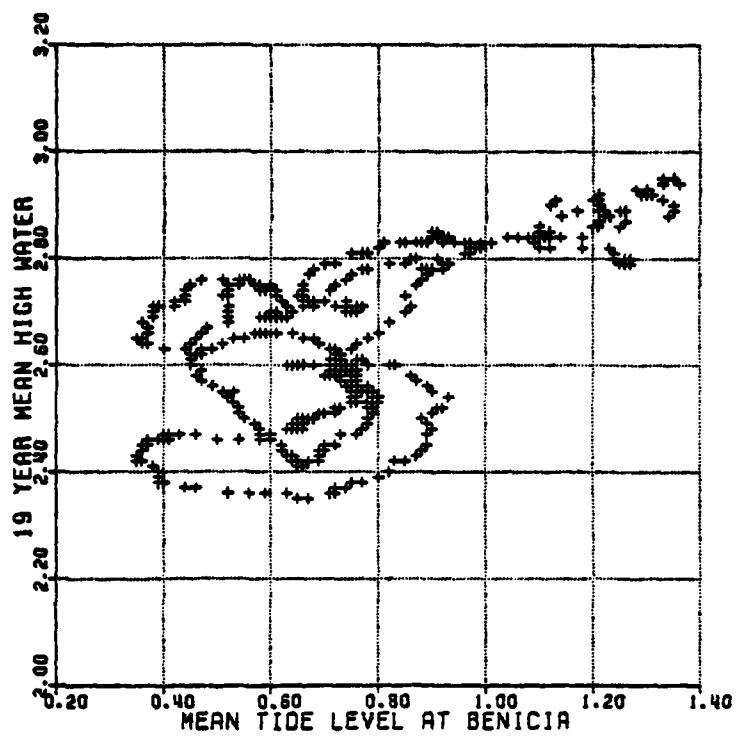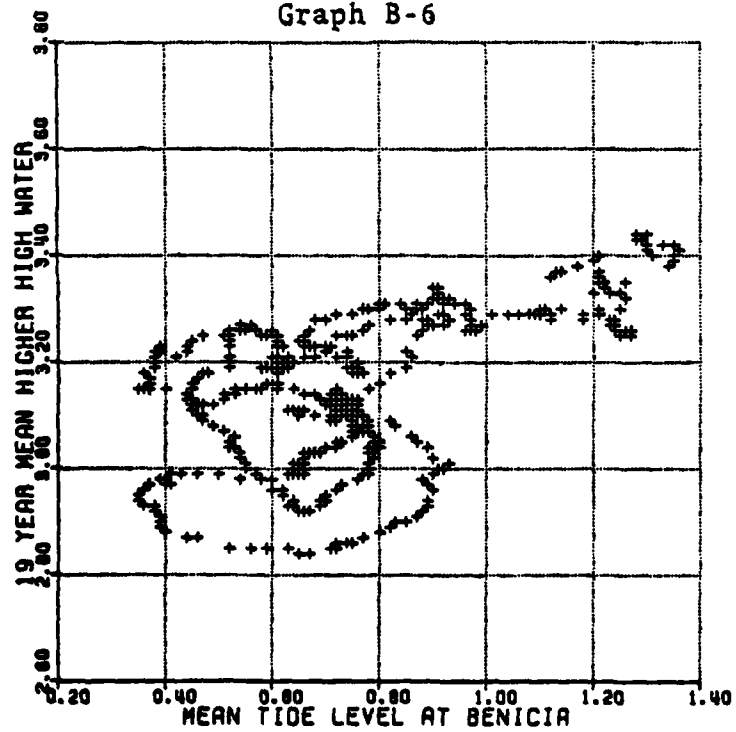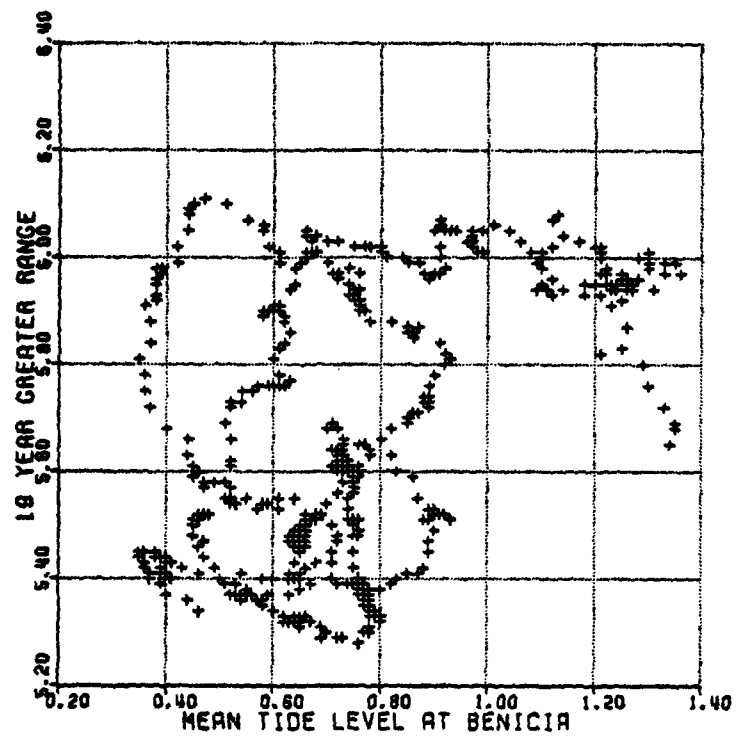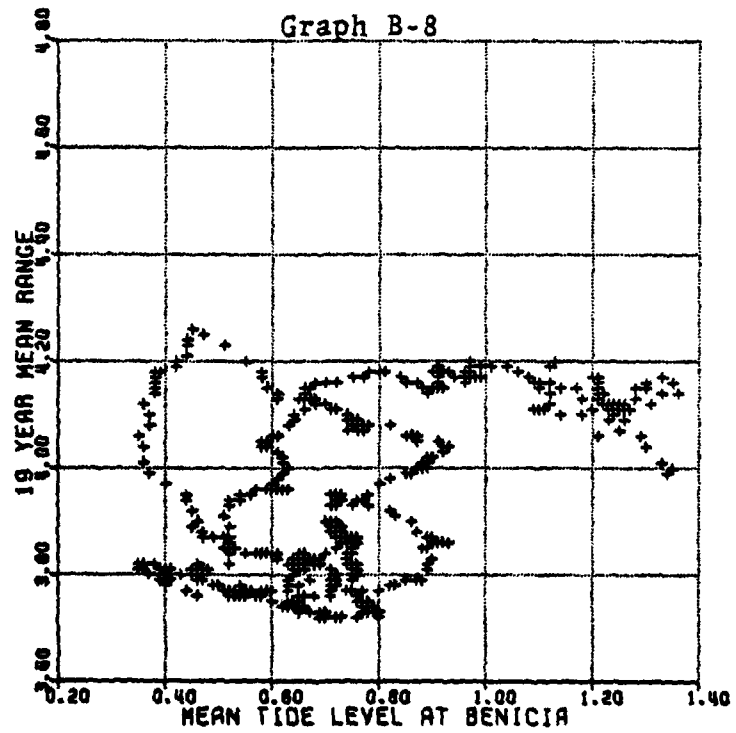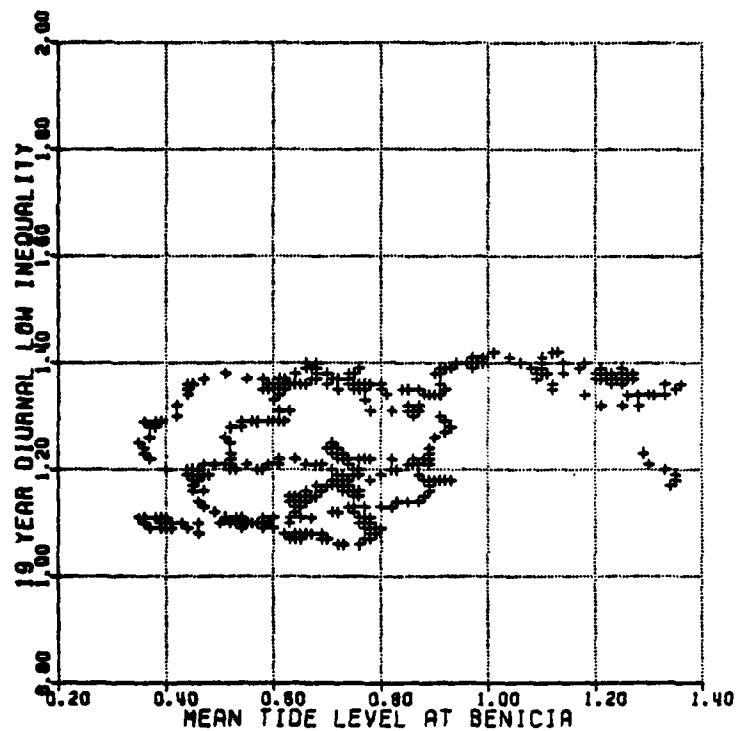
Graph B-10


Graph B-11

129
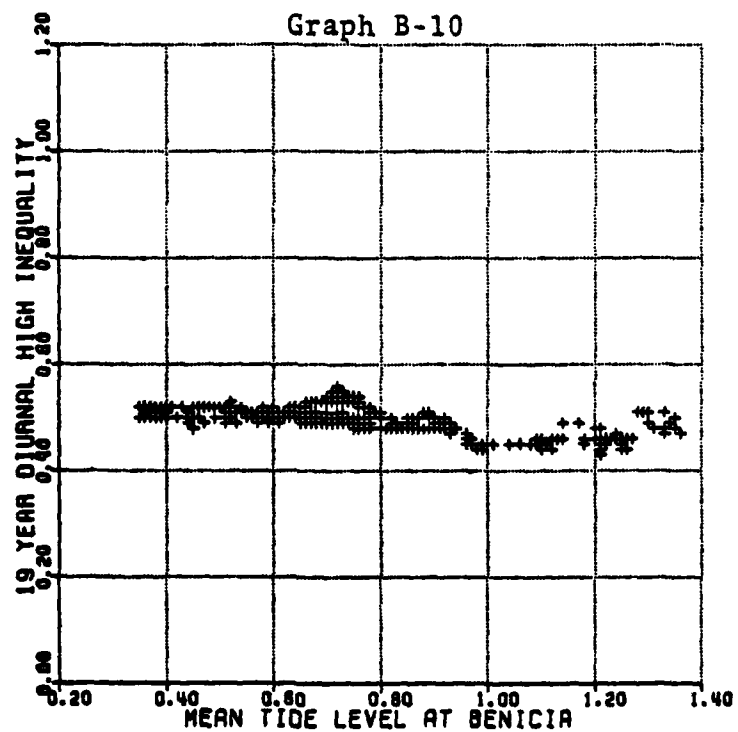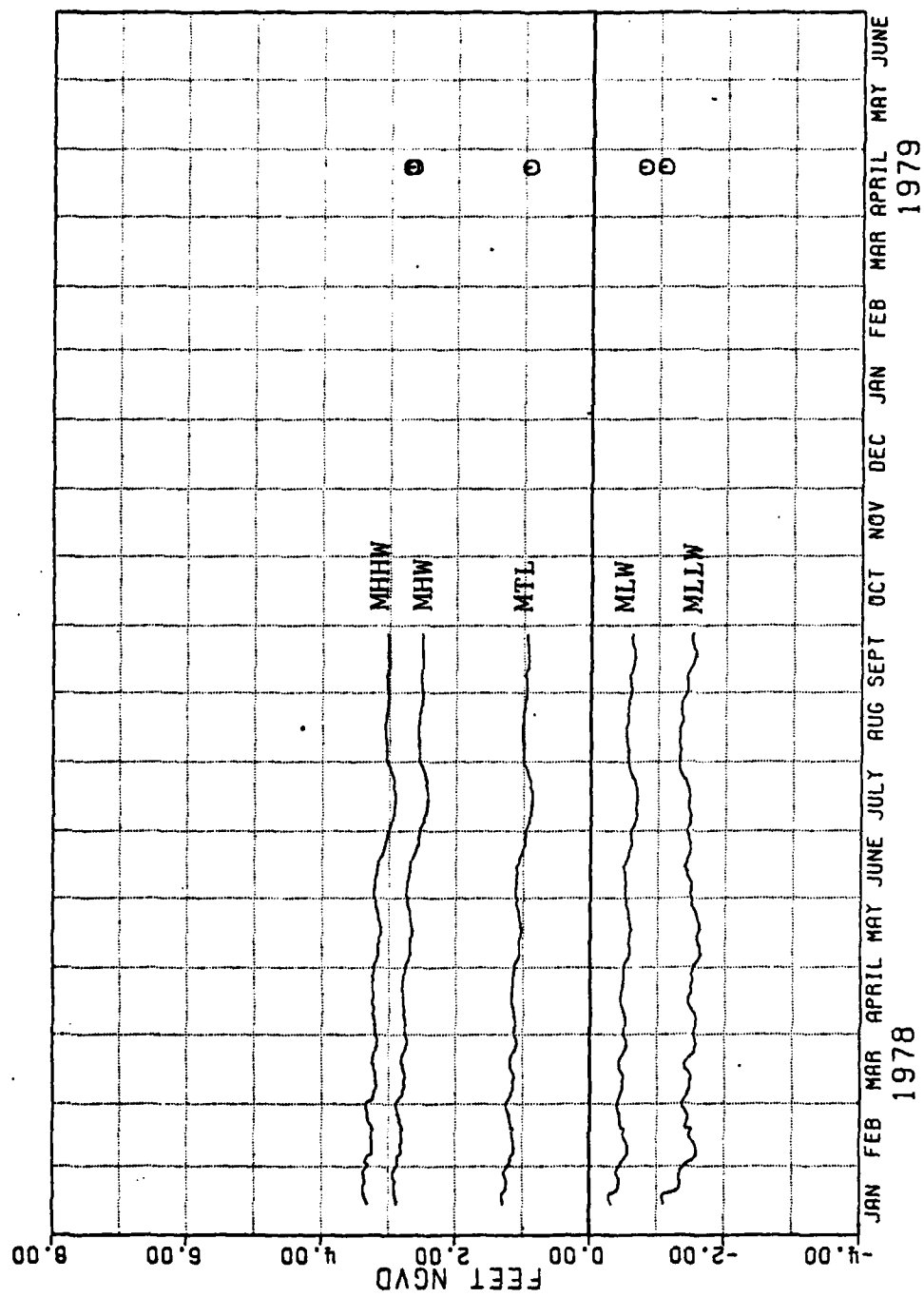
Graph M-1. 19-YEAR TIDAL DATUMS AT MALLARD ISLAND.
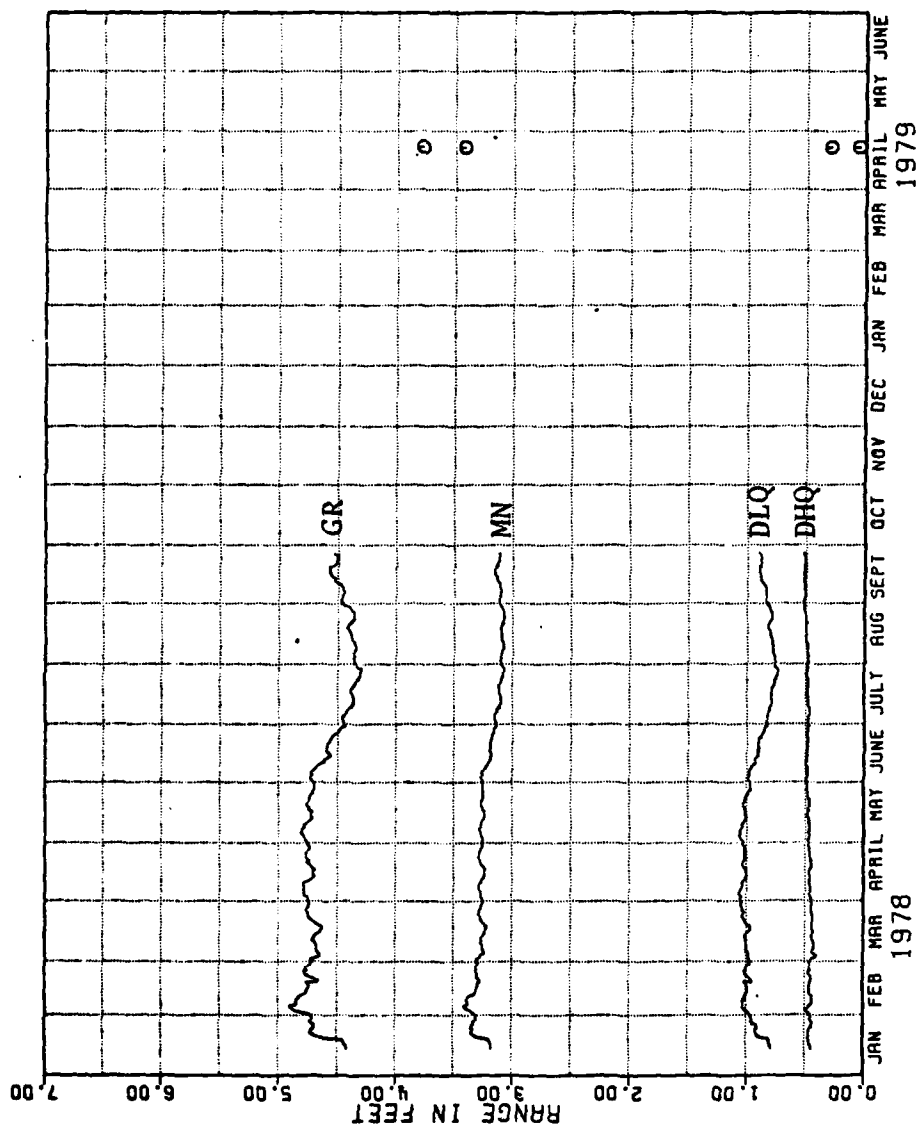
Graph M-2. 19-YEAR TIDAL RANGES AT MALLARD ISLAND.

131

Graph M-3

132

Graph M-4



Graph M-5

133

Graph M-6



Graph M-7

134

Graph M-8



Graph M-9

135
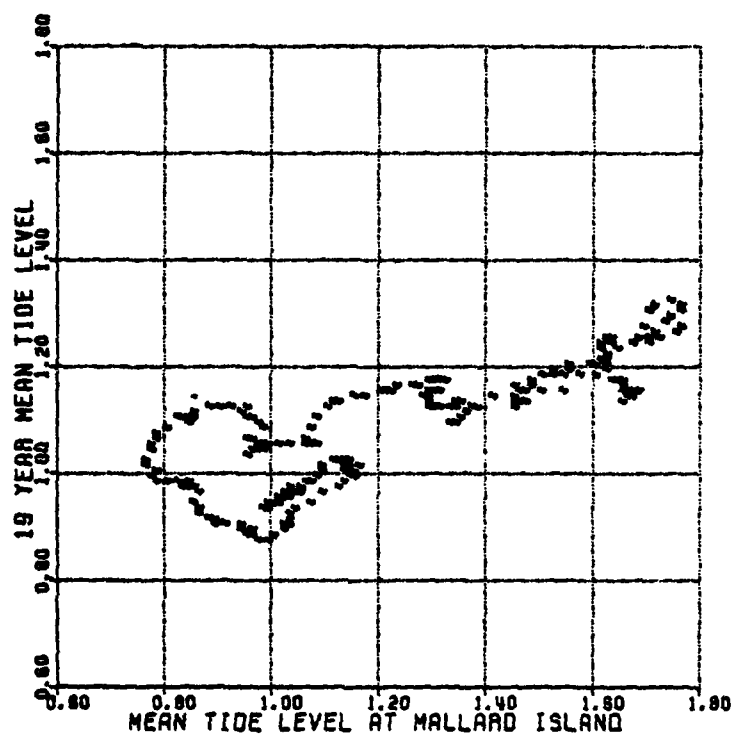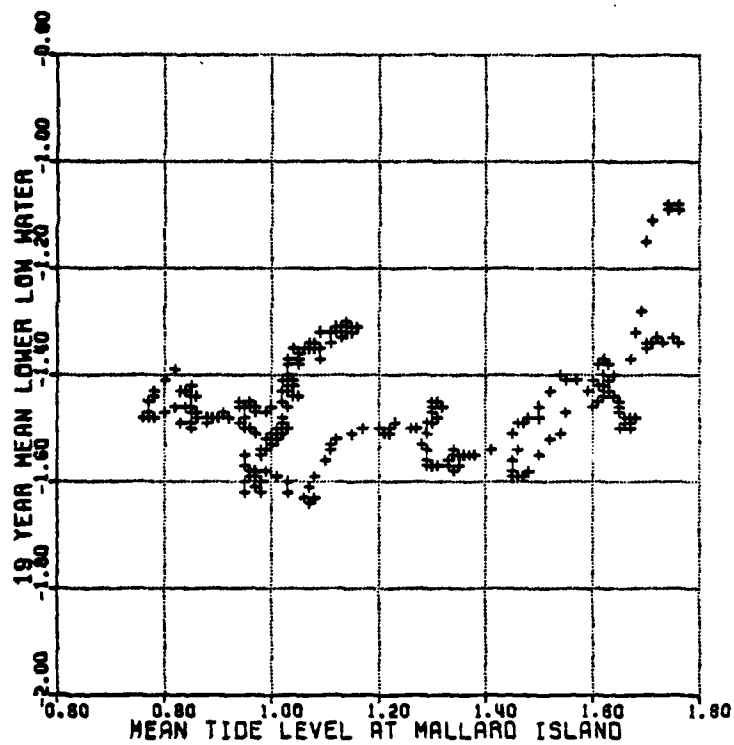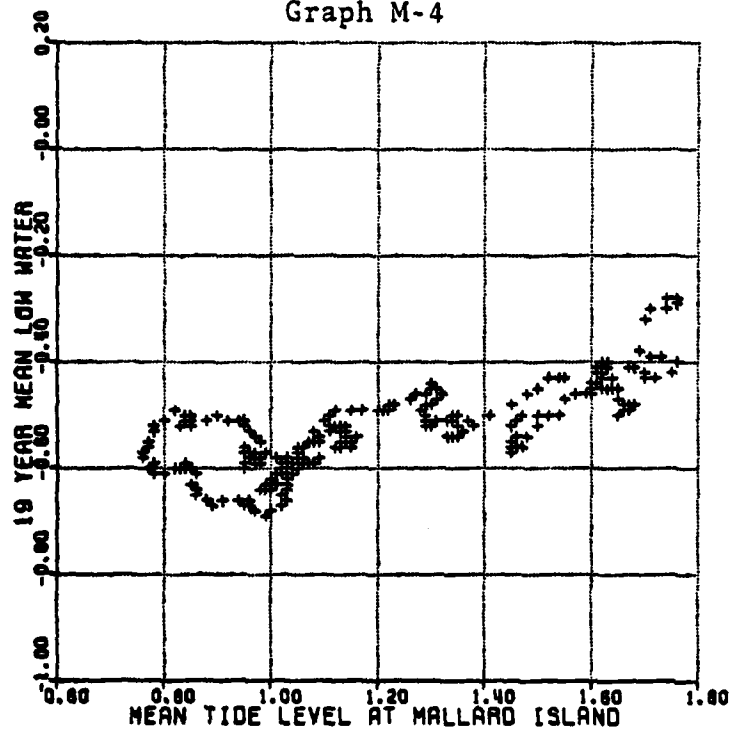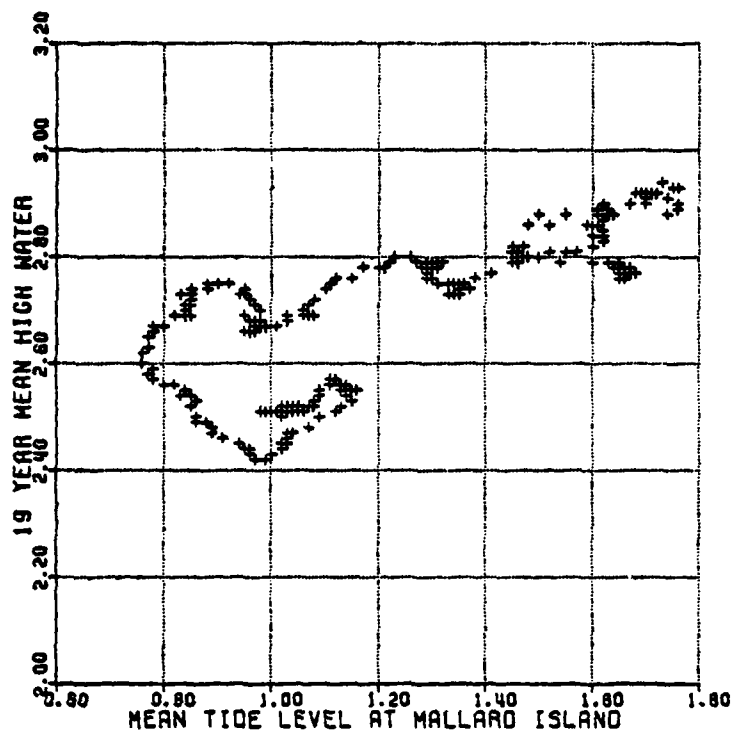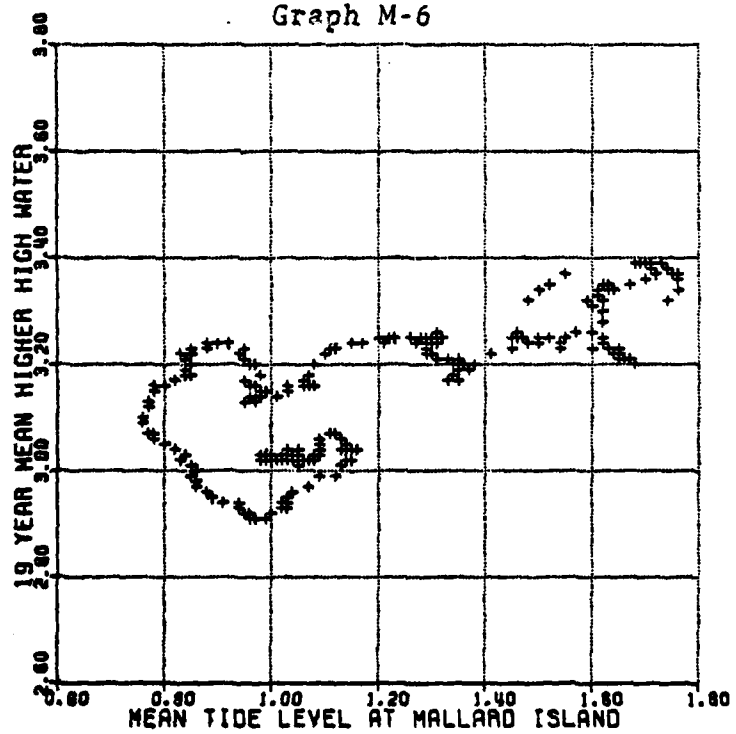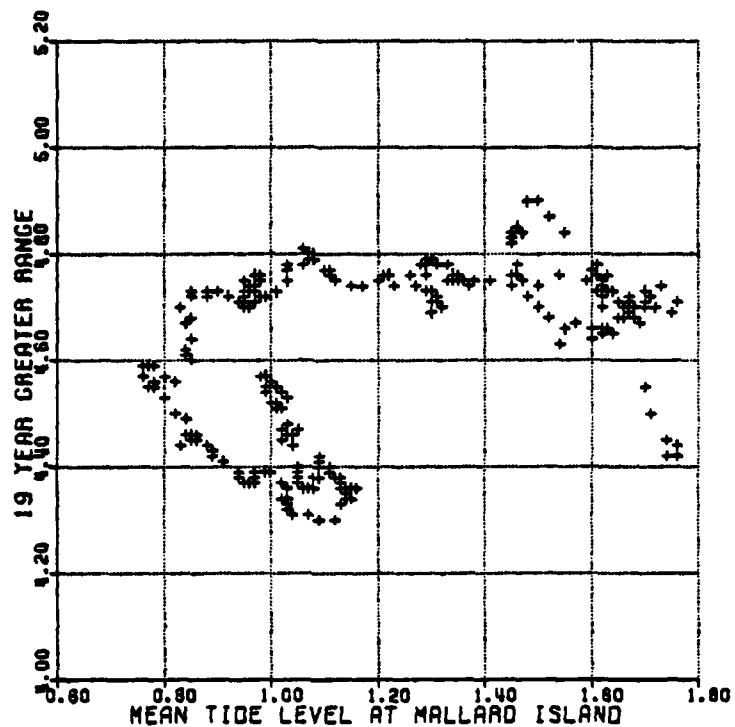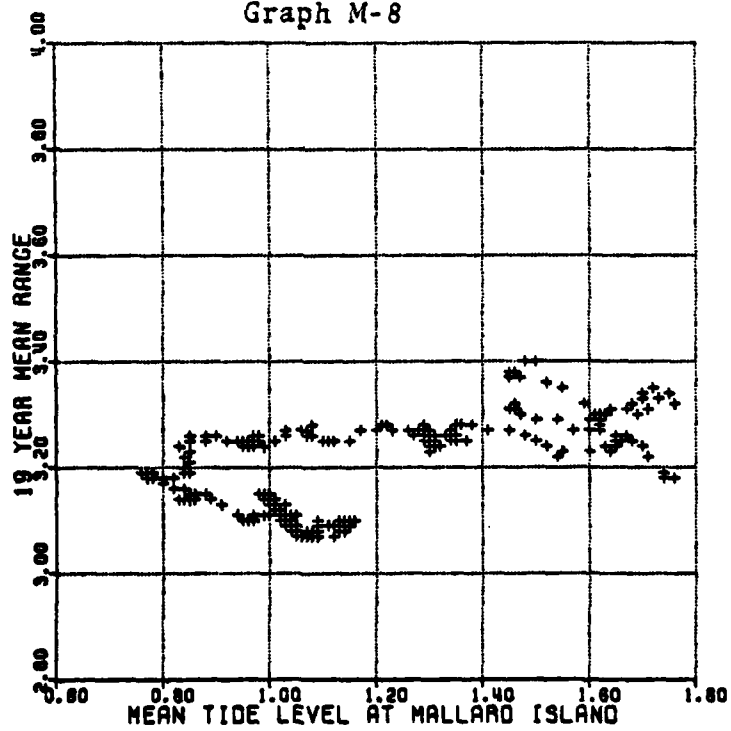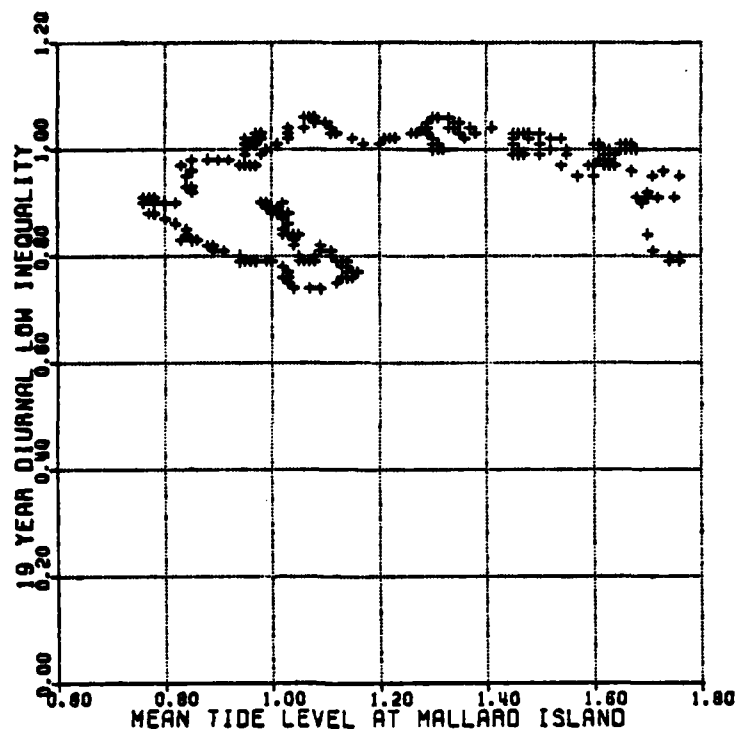
Graph M-10



Graph M-11

136
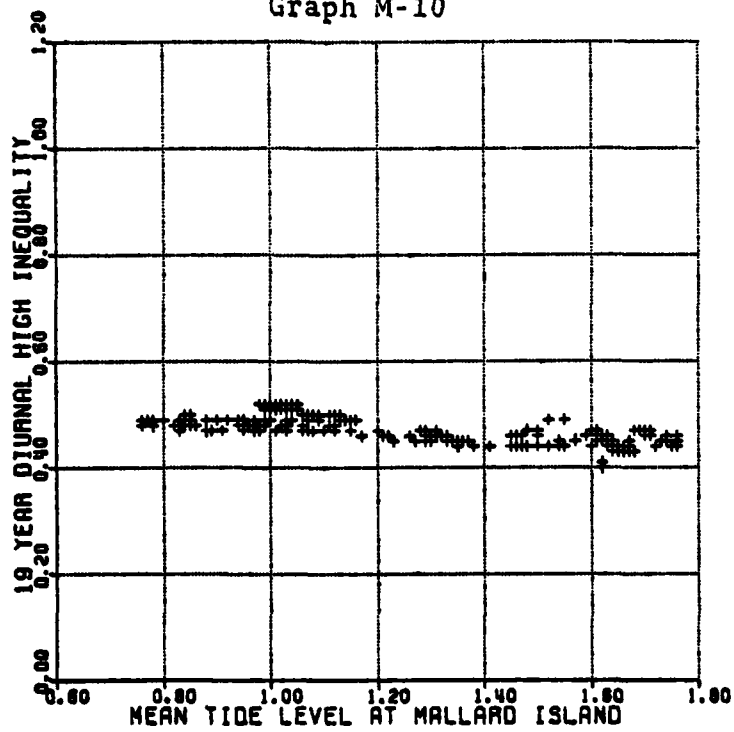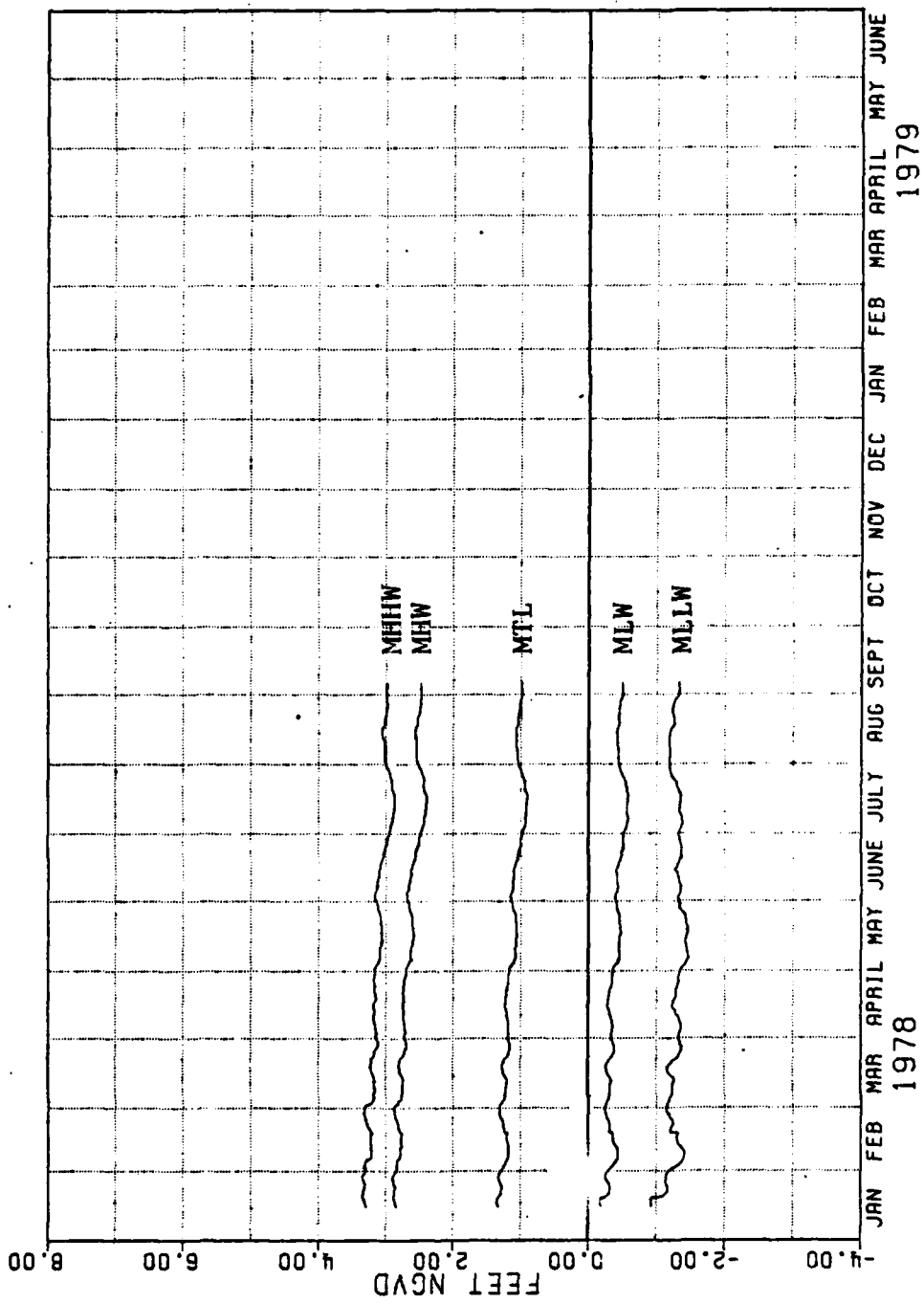
Graph C-1. 19-YEAR TIDAL DATUMS AT COLLINSVILLE.
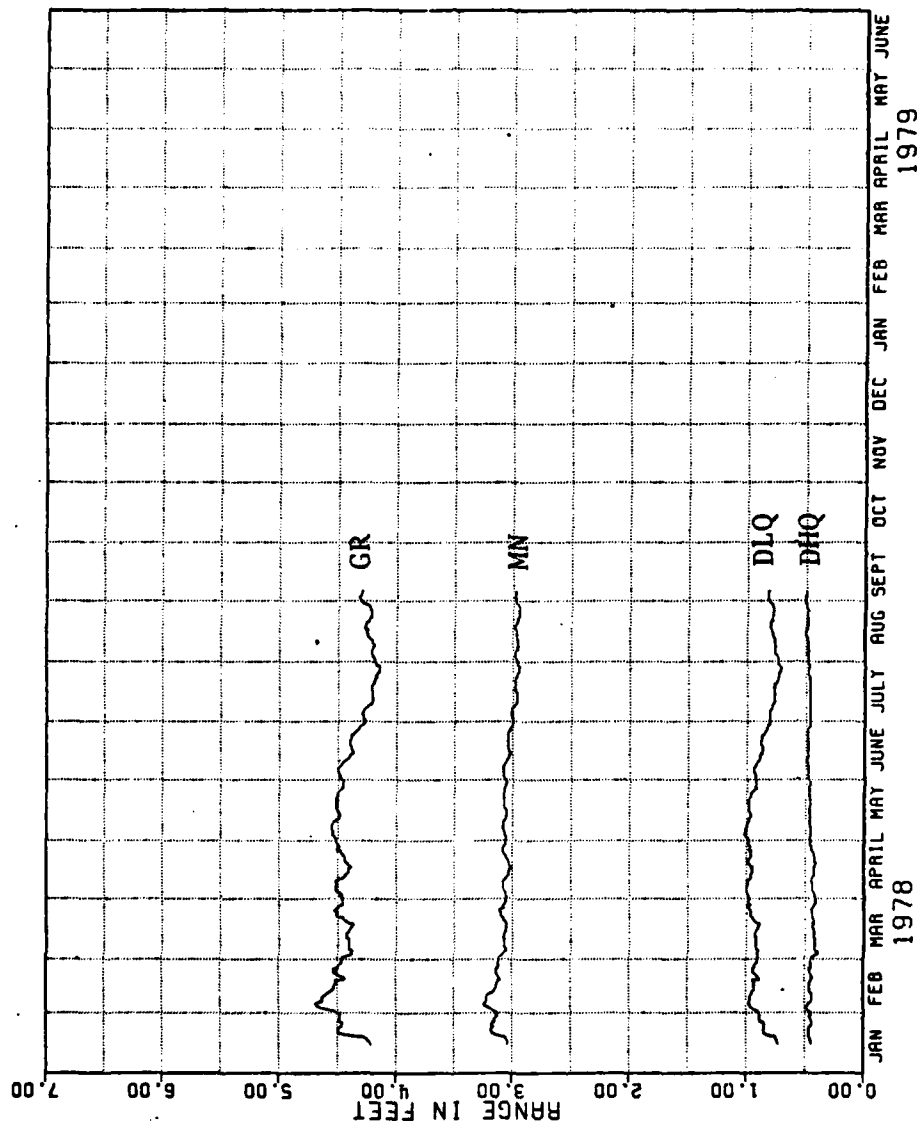
Graph C-2.   19-YEAR TIDAL RANGES AT COLLINSVILLE.

138
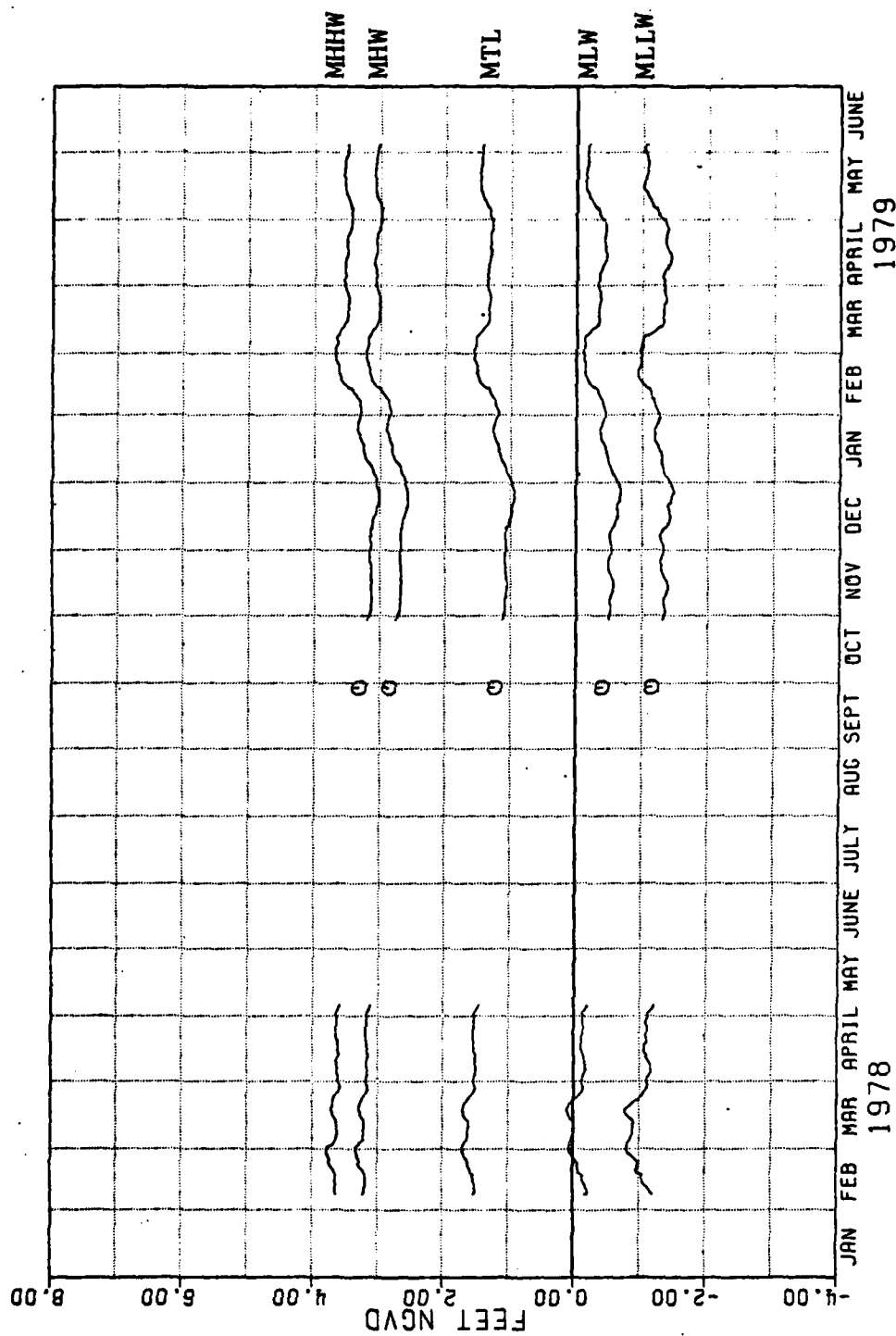
Graph T-1. 19-YEAR TIDAL DATUMS AT THREE MILE SLOUGH.
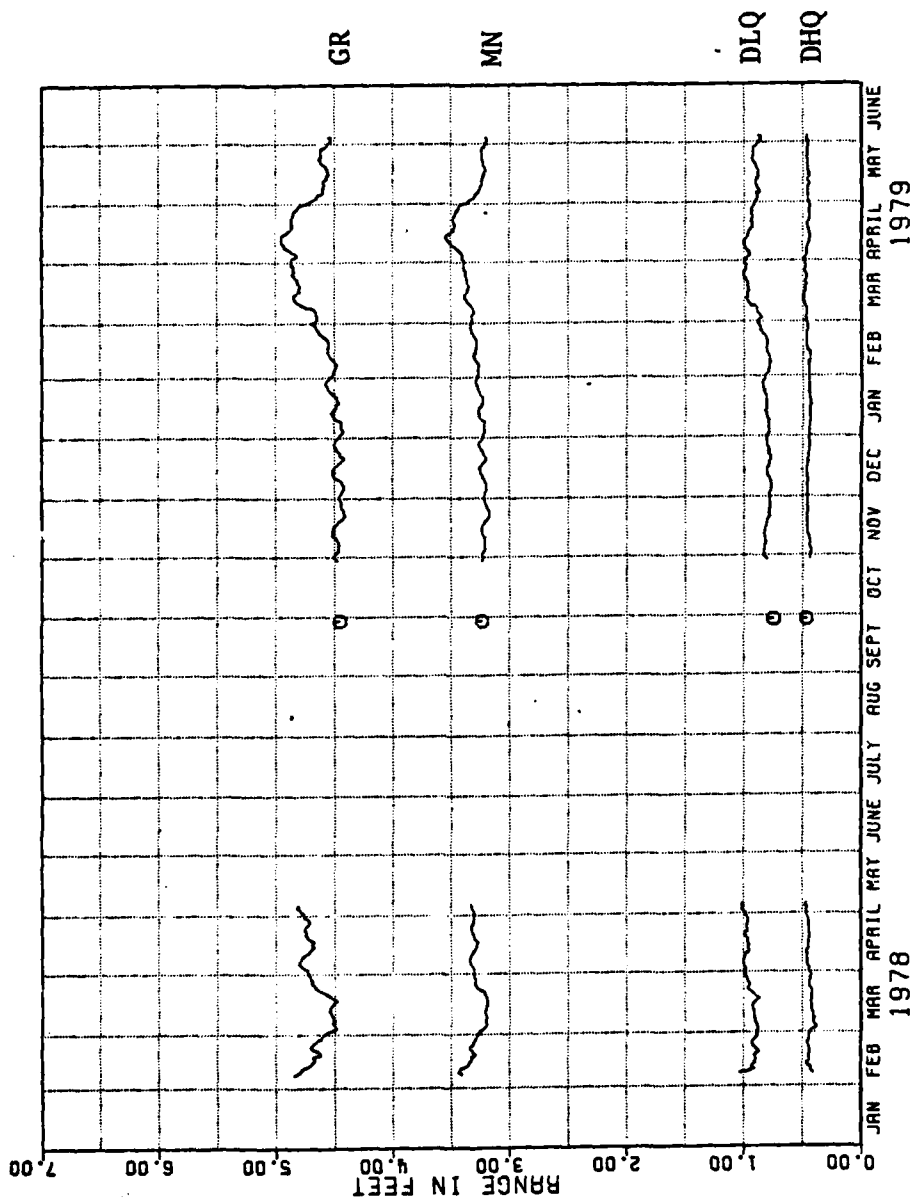
Graph T-2. 19-YEAR TIDAL RANGES AT THREE MILE SLOUGH.

140

Graph T-3

141

Graph T-4



Graph T-S

142

Graph T-6



Graph T-7

143

Graph T-8



Graph T-9

144
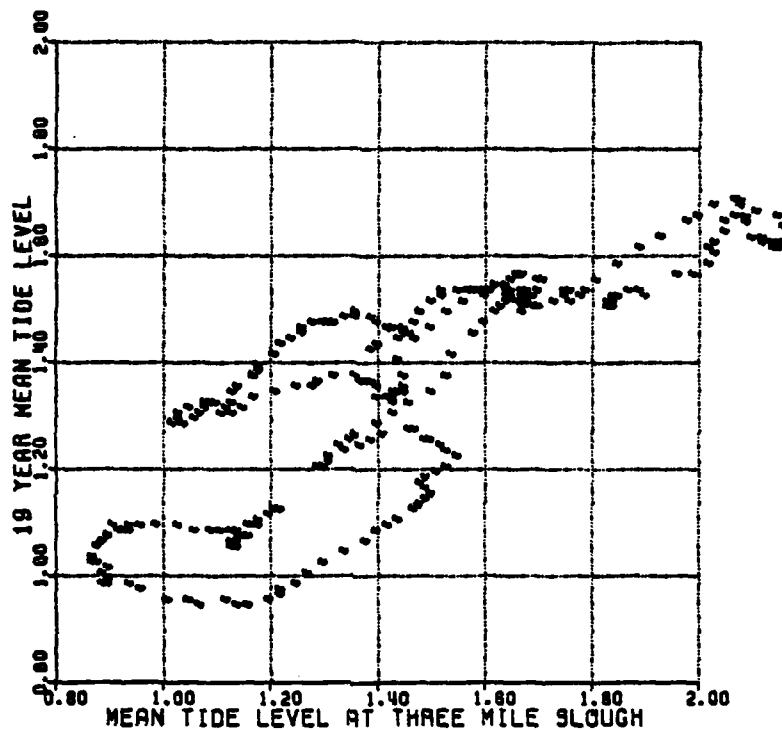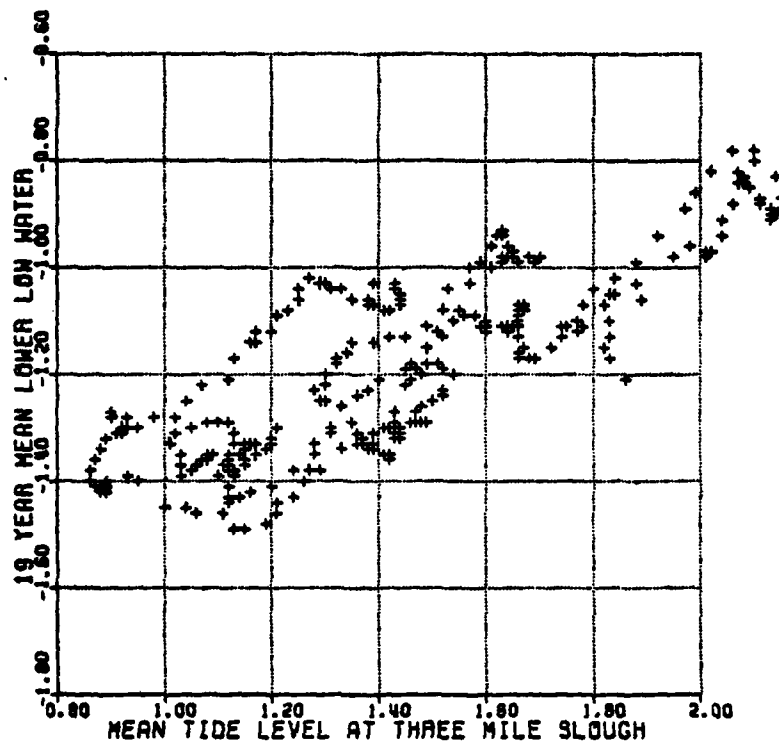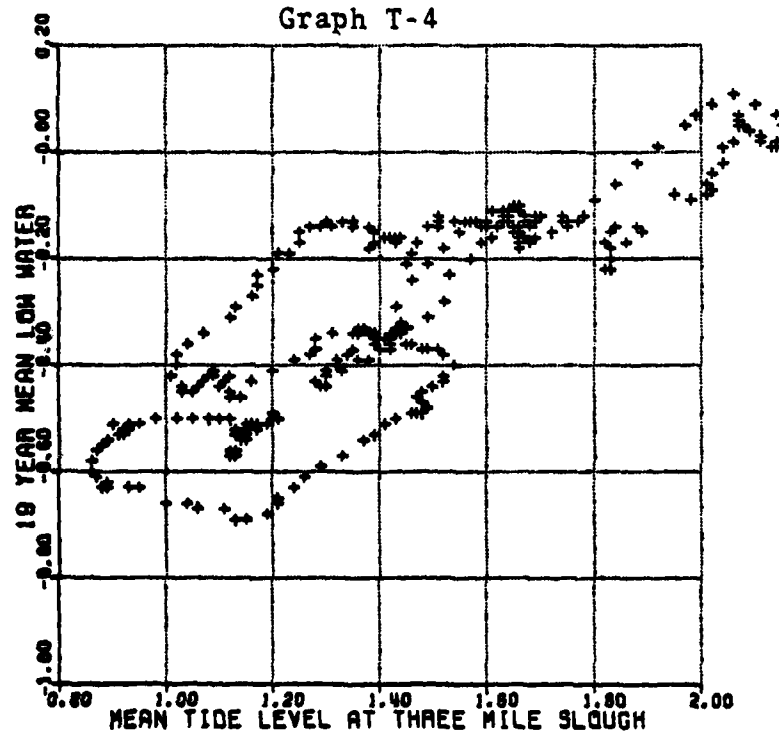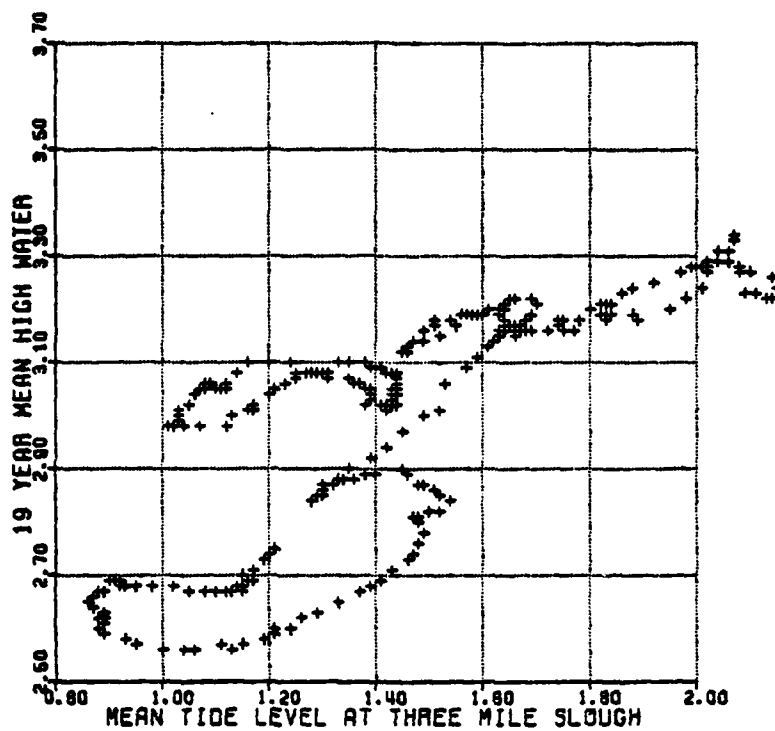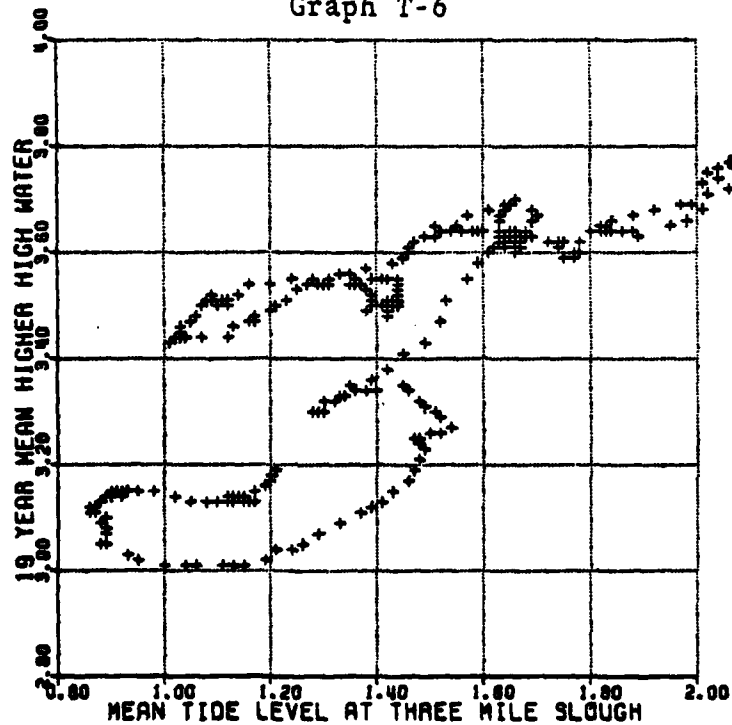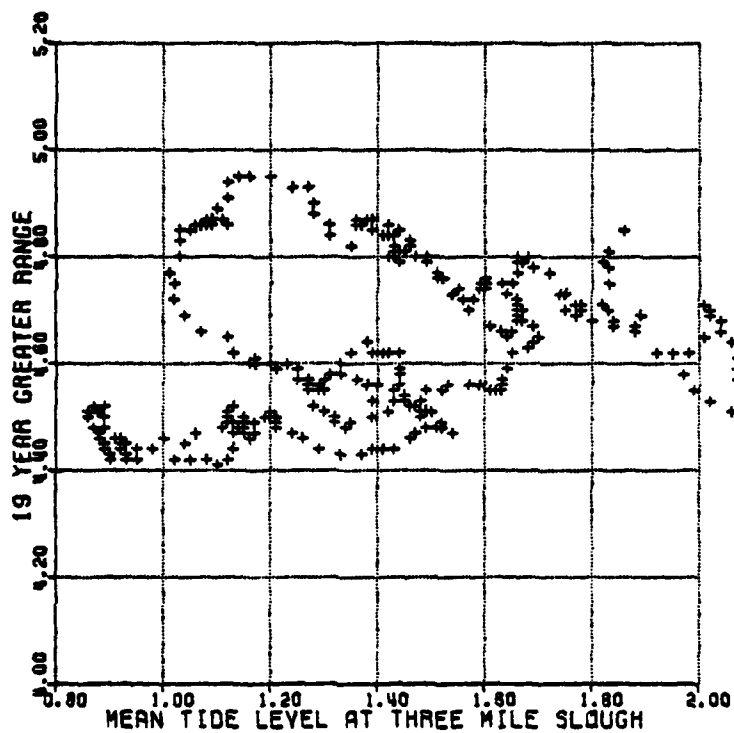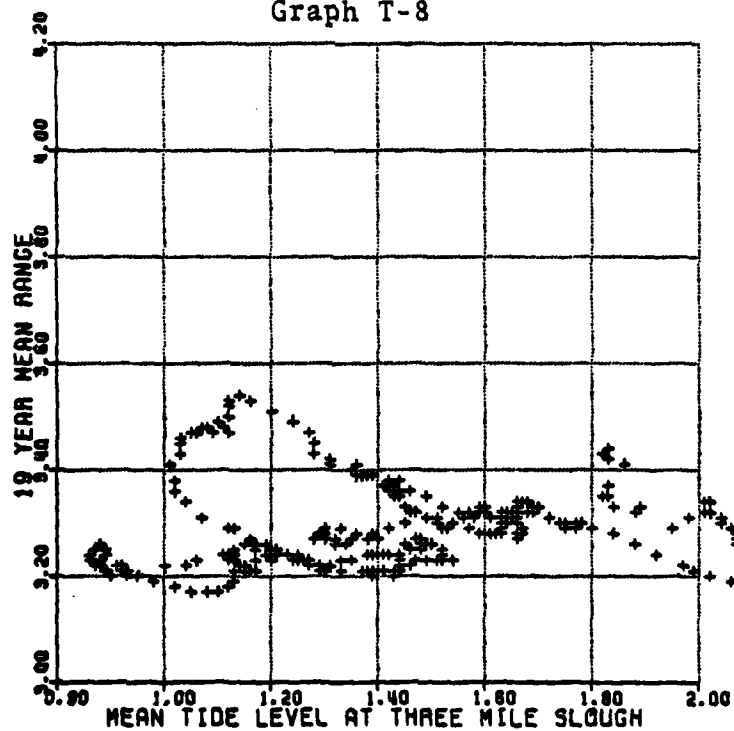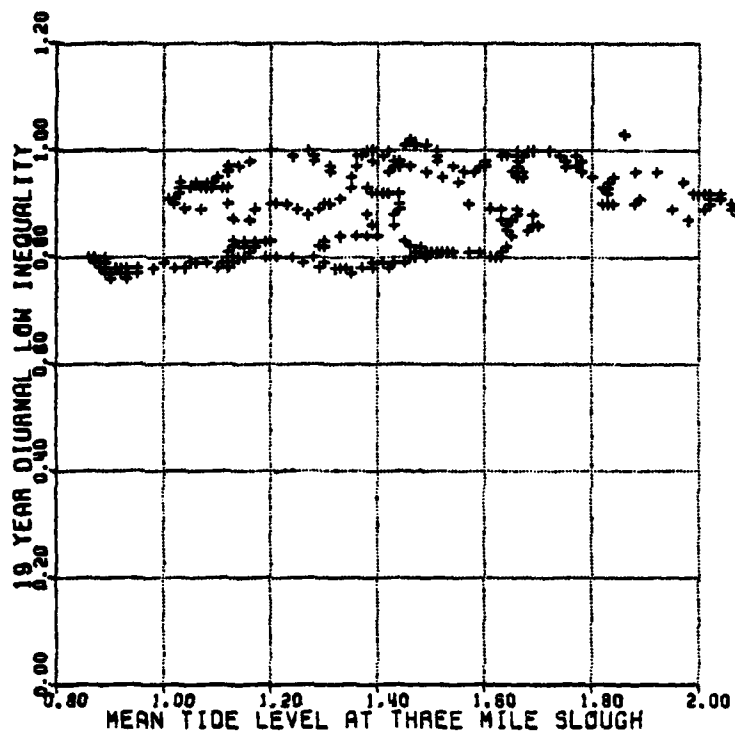
Graph T-10



Graph T-11

145
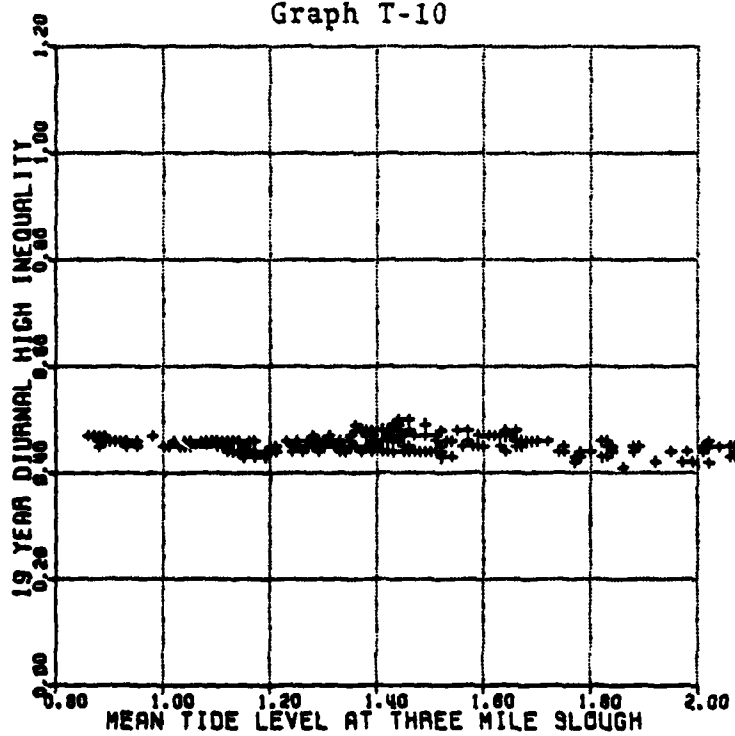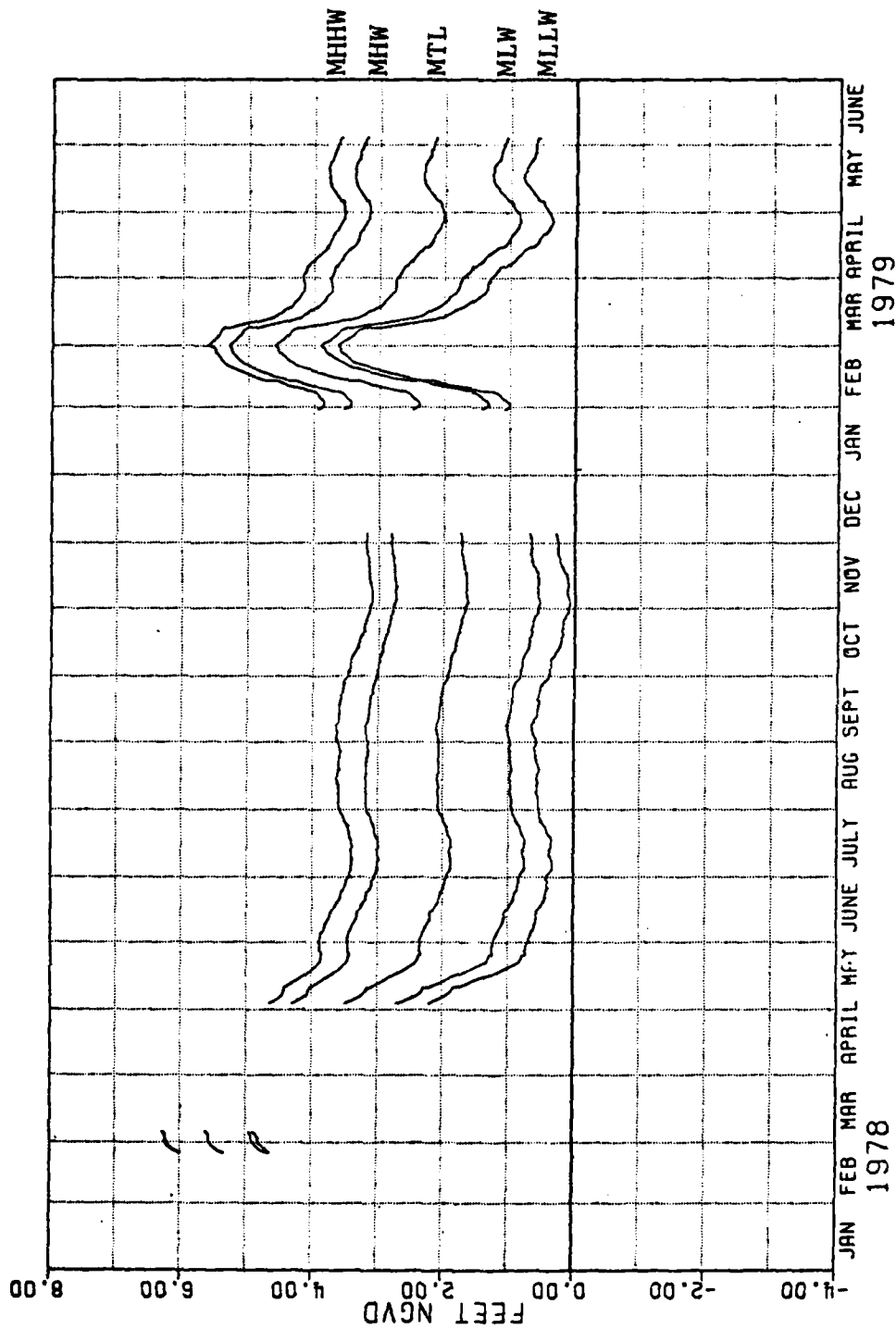
Graph W-1. 19-YEAR TIDAL DATUMS AT WALNUT GROVE.

146
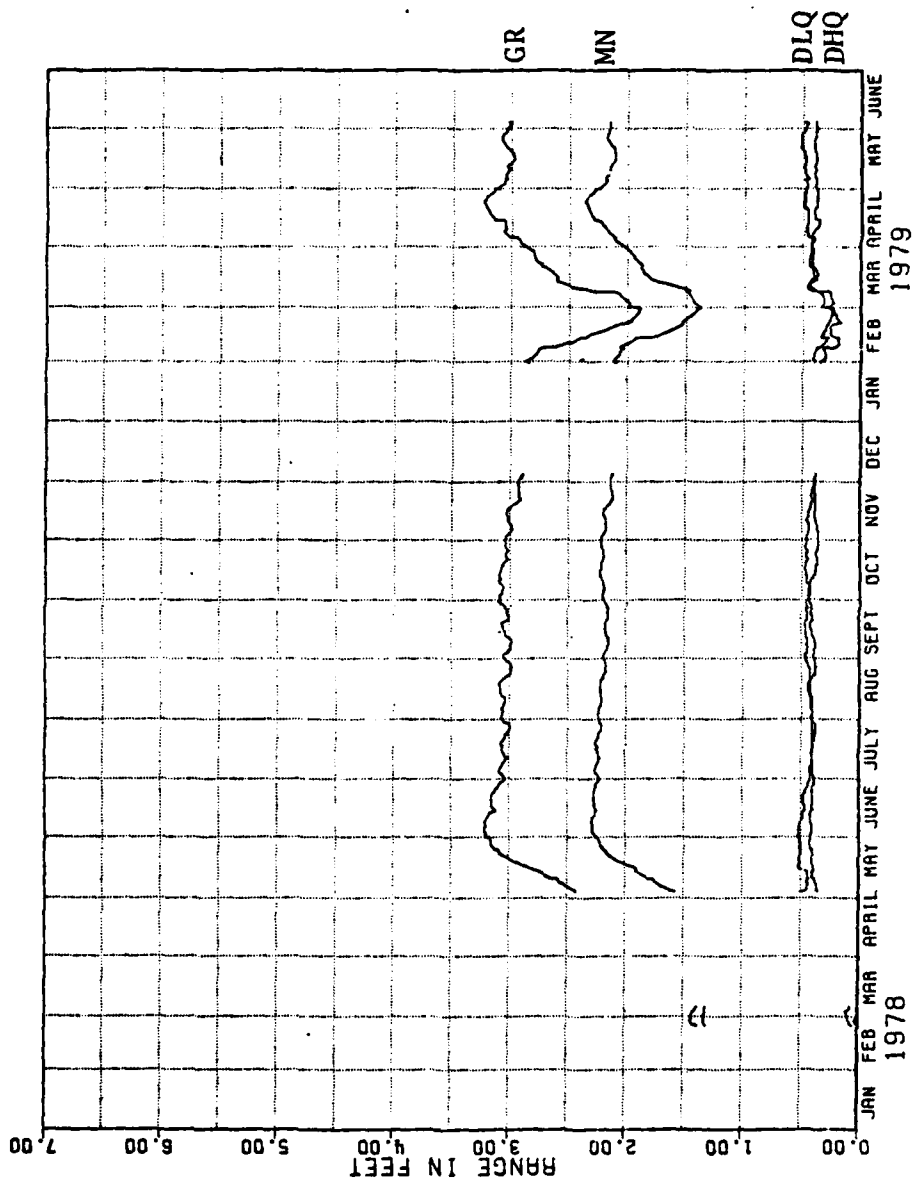
Graph W-2.  19-YEAR TIDAL RANGES AT WALNUT GROVE.
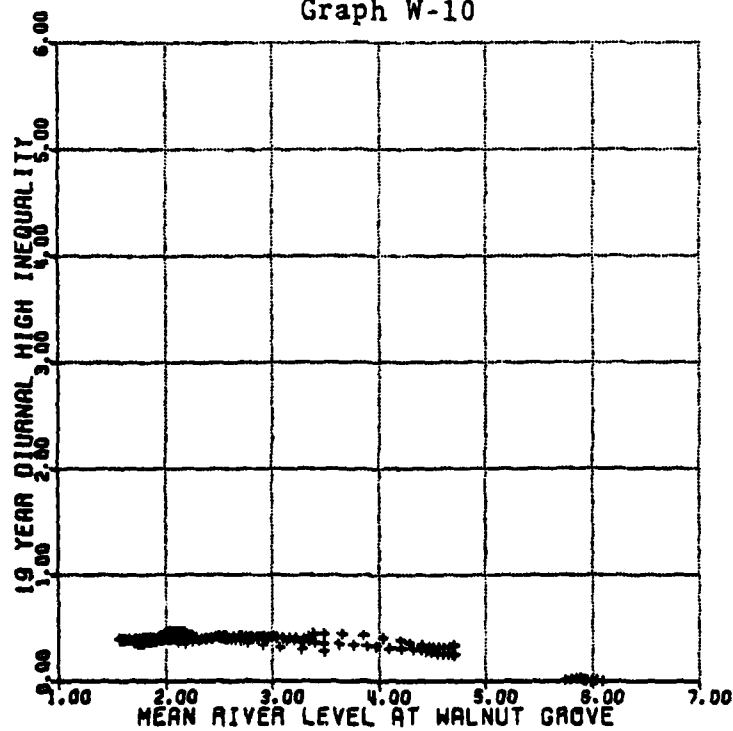
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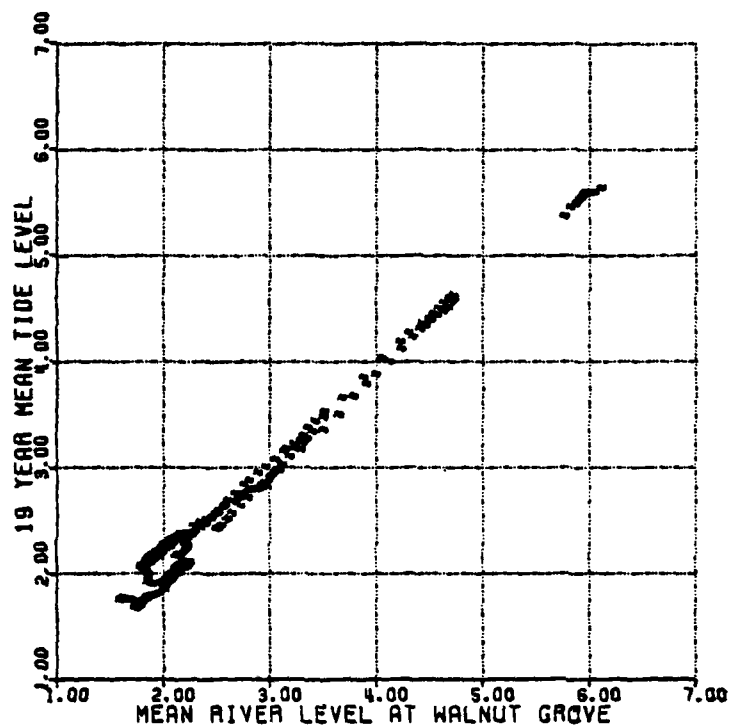
Graph W-3

Graph W-4



Graph W-5

149
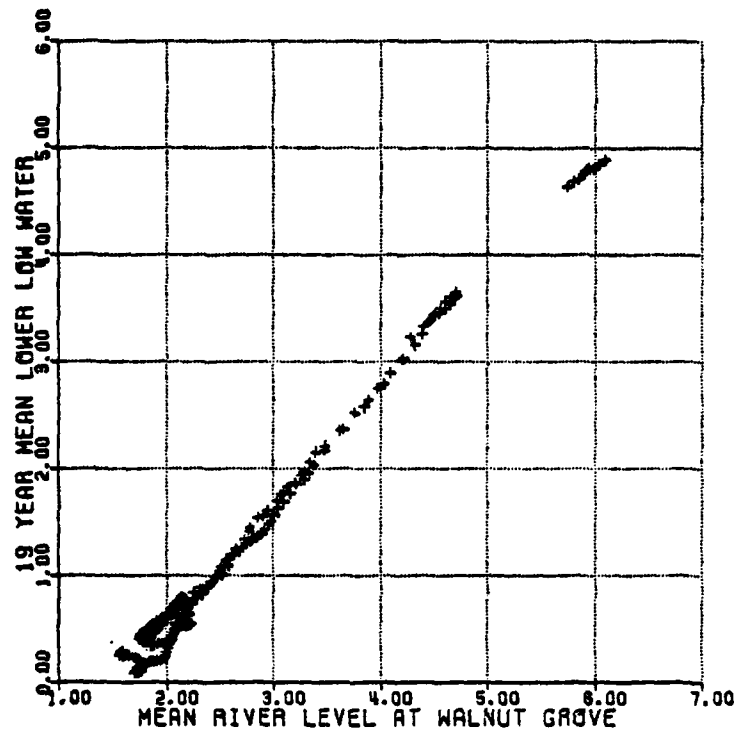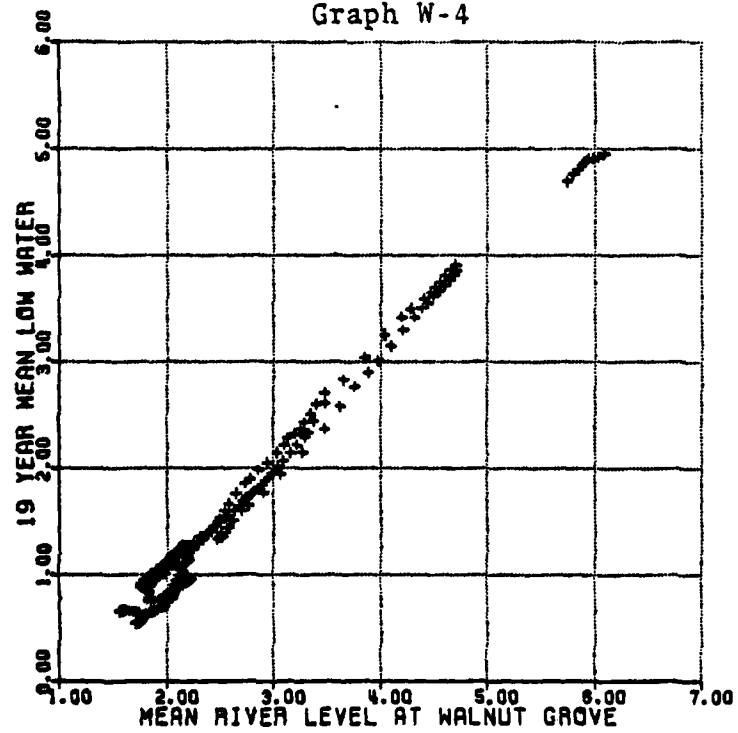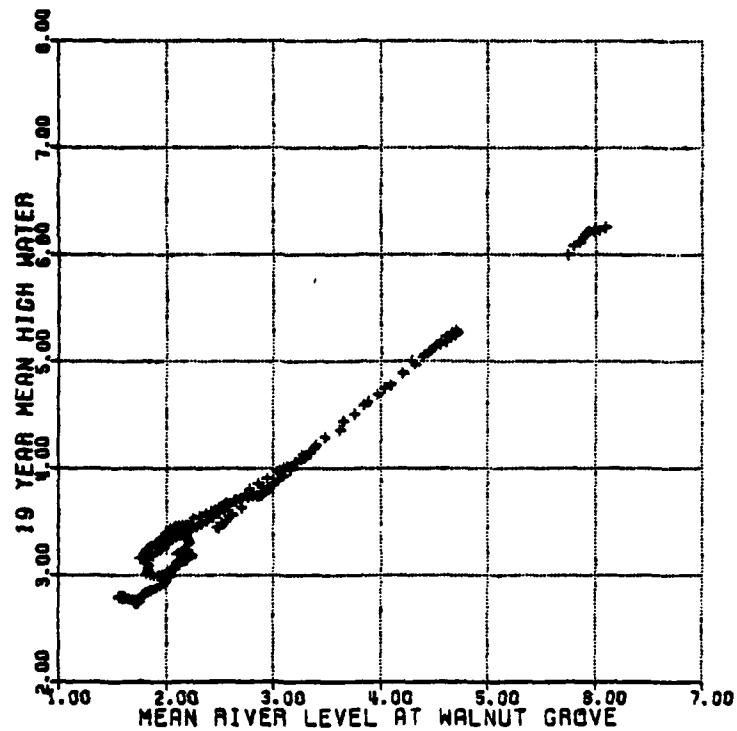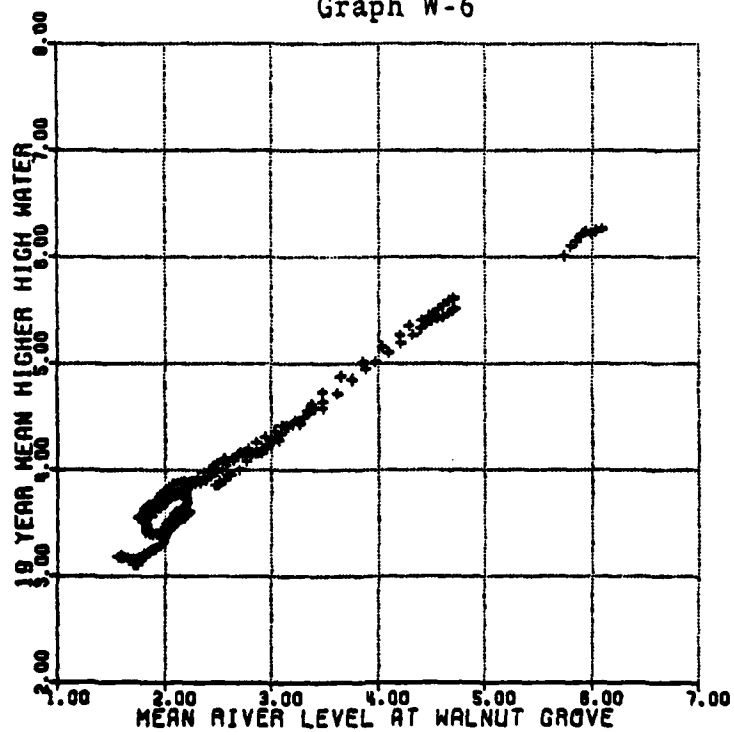
Graph W-6



Graph W-7

Graph W-8



Graph W-9

151
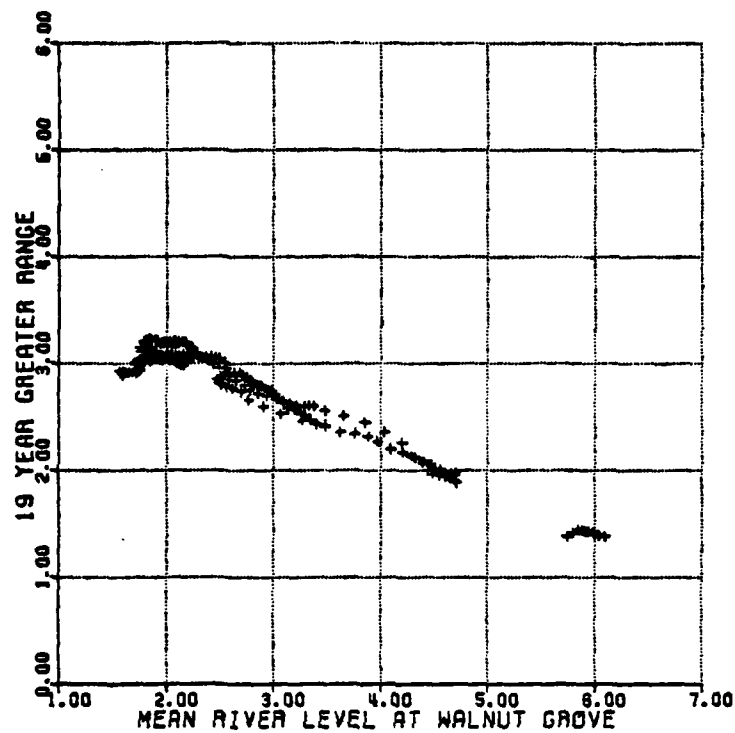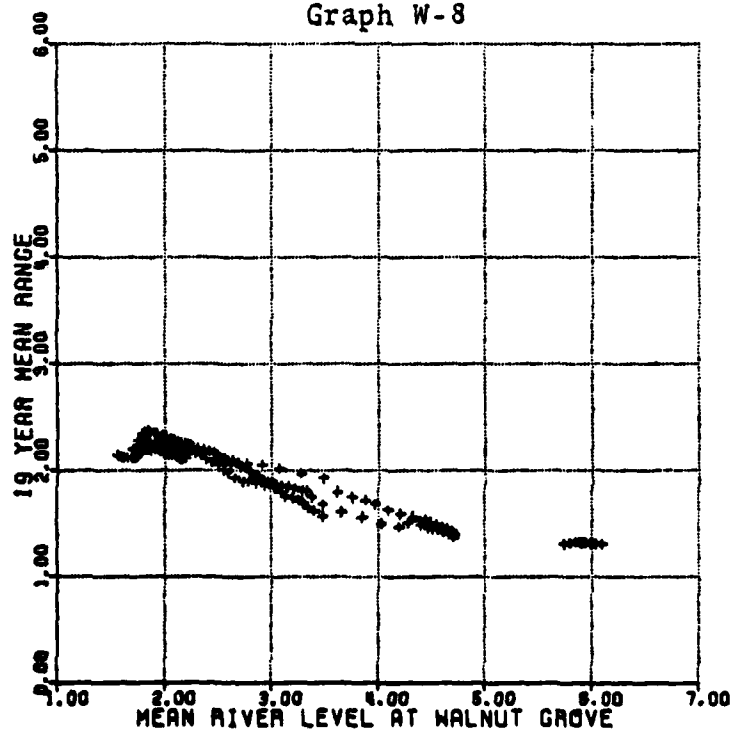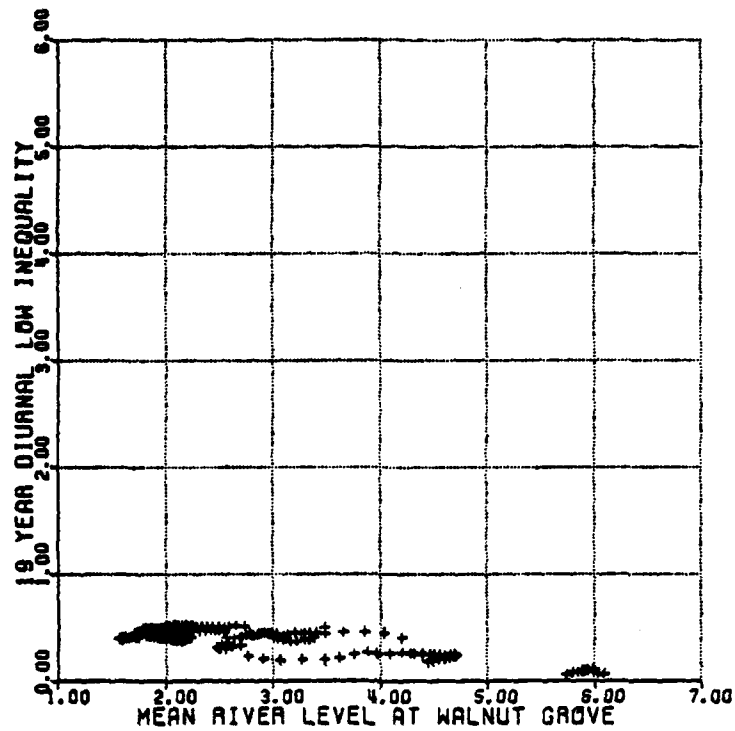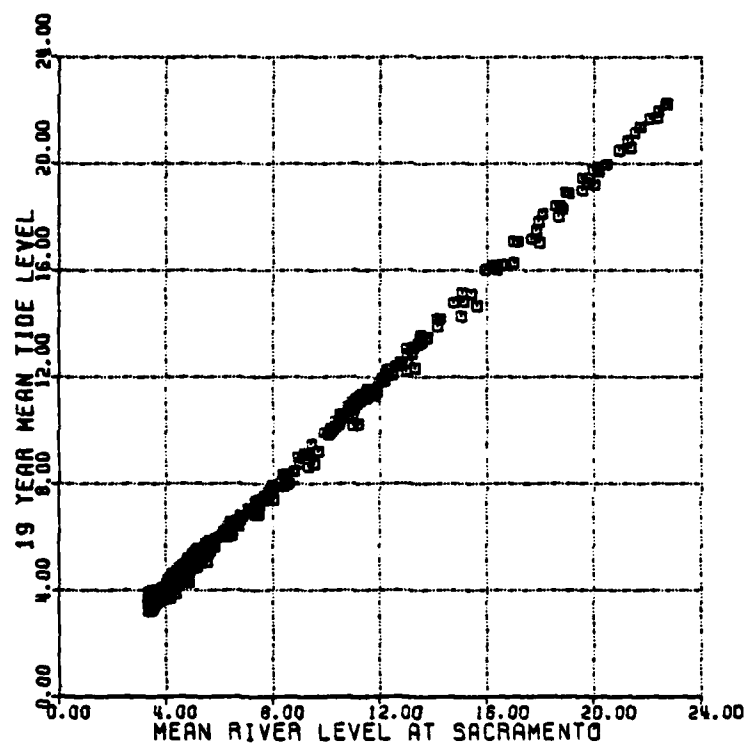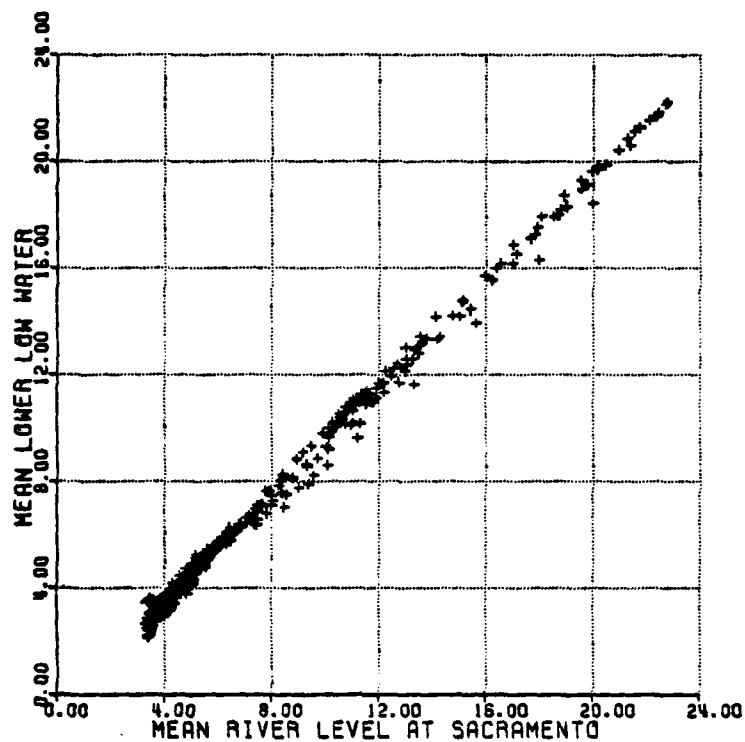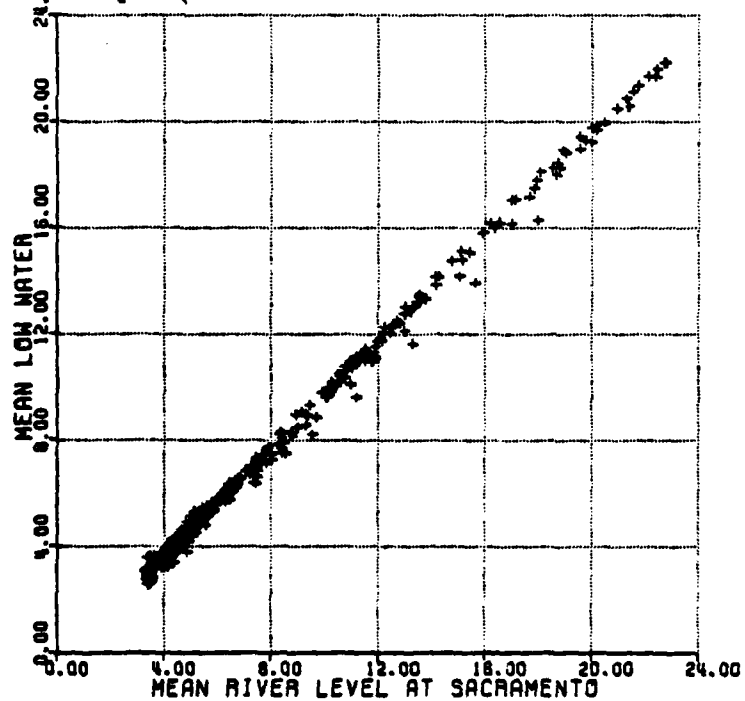
Graph W-10



Graph W-11

152

Graph Q-3.   FROM 7-DAY COMPARISONS

Graph Q-4.    FROM 7-DAY COMPARISONS



Graph Q-5.    FROM 7-DAY COMPARISONS

154

Graph Q-6.   FROM 7-DAY COMPARISONS



Graph Q-7.   FROM 7-DAY COMPARISONS

155

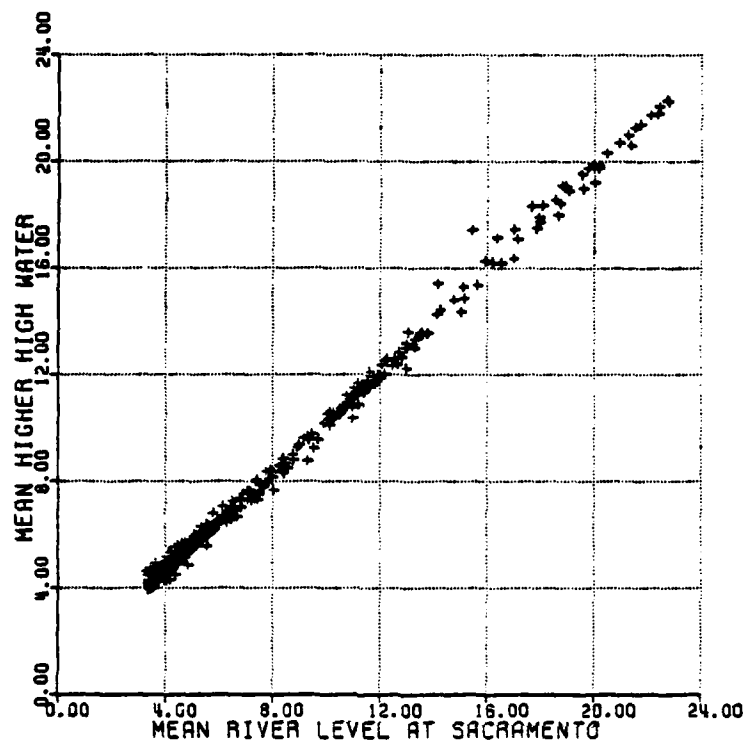Graph Q-8. FROM 7-DAY COMPARISONS



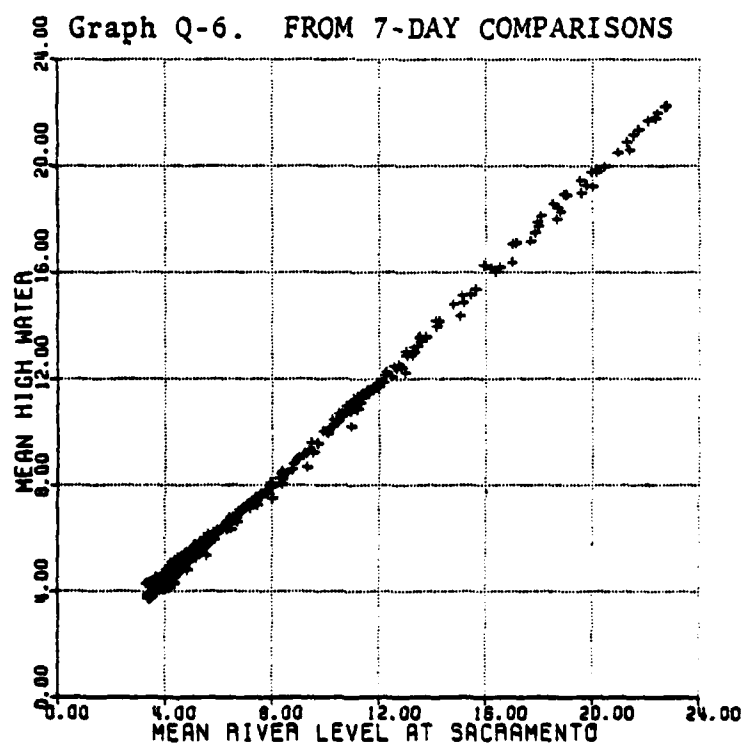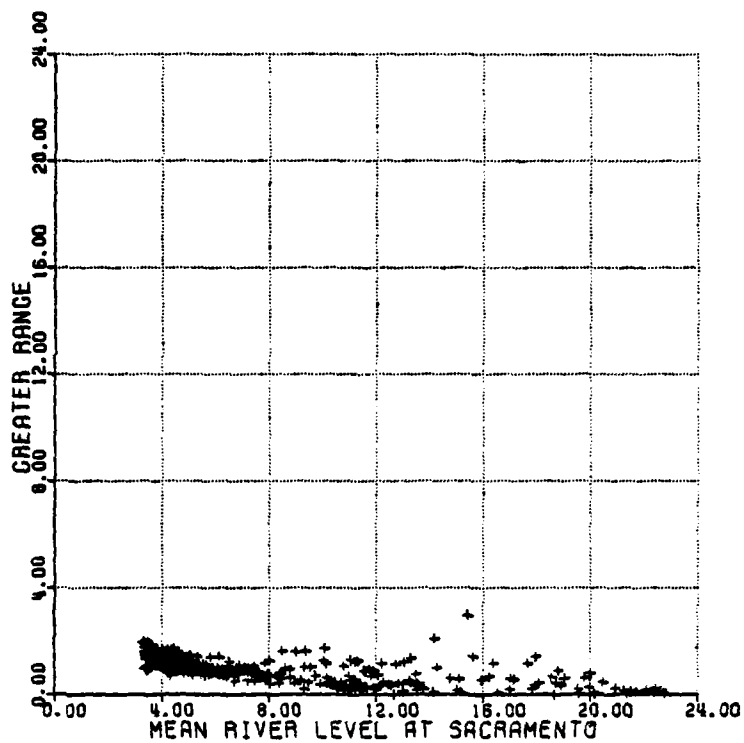Graph Q-9. FROM 7-DAY COMPARISONS

156

Graph Q-10.   FROM 7-DAY COMPARISONS



Graph Q-11.   FROM 7-DAY COMPARISONS

157

Graph R-3.   FROM 14-DAY COMPARISONS

Graph R-4.   FROM 14-DAY COMPARISONS



Graph R-5.   FROM 14-DAY COMPARISONS

159

Graph R-6.    FROM 14-DAY COMPARISONS
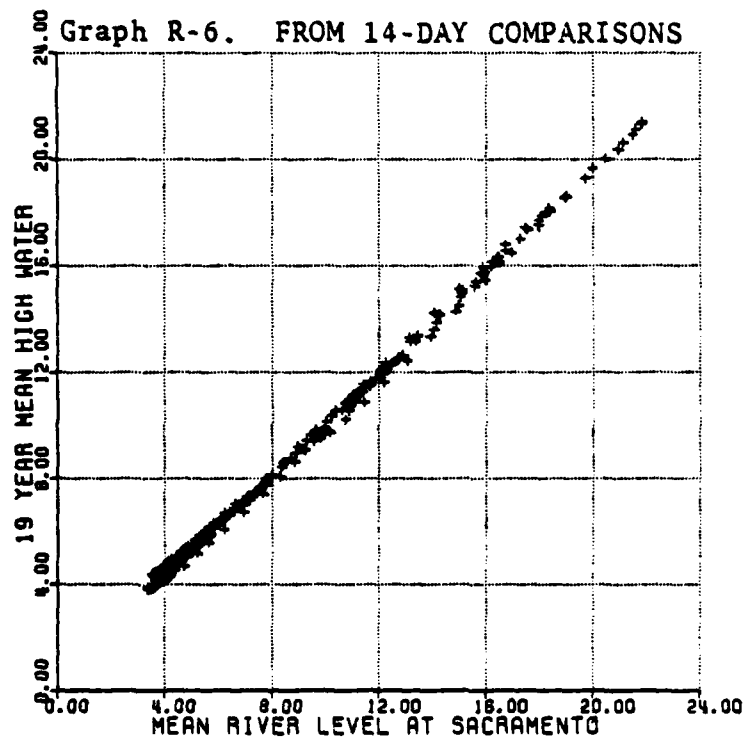


Graph R-7.    FROM 14-DAY COMPARISONS

160
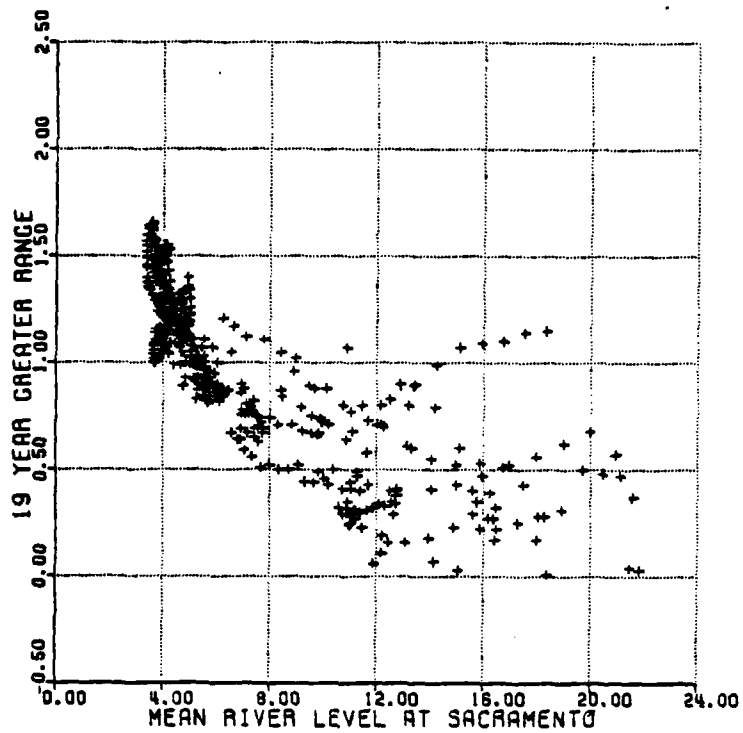
Graph R-8. FROM 14-DAY COMPARISONS



Graph R-9. FROM 14-DAY COMPARISONS

161

Graph R-10.  FROM 14-DAY COMPARISONS



Graph R-11.  FROM 14-DAY COMPARISONS

162

Graph S-3

163

Graph S-4



Graph S-5

164

Graph S-6


Graph S-7

165

Graph S-8



Graph S-9

166
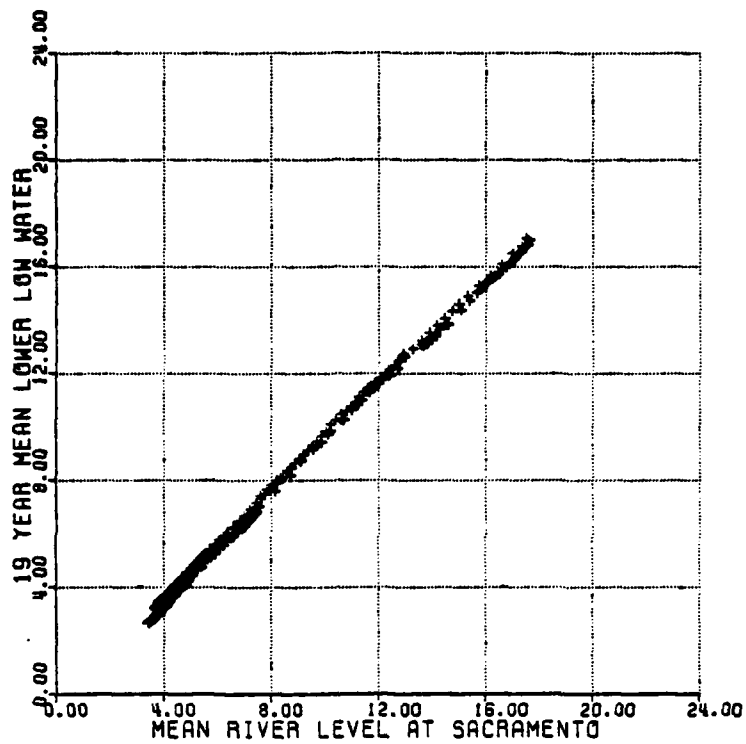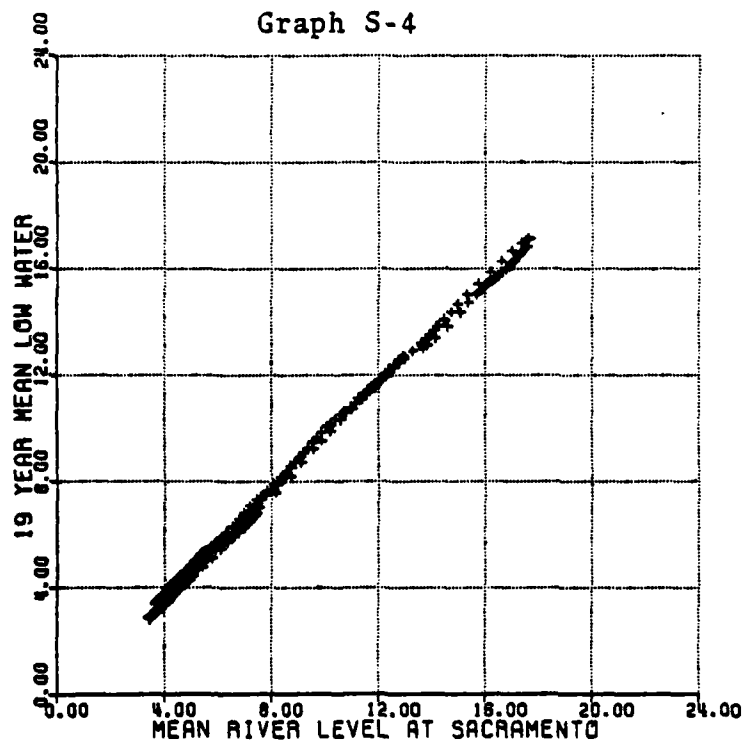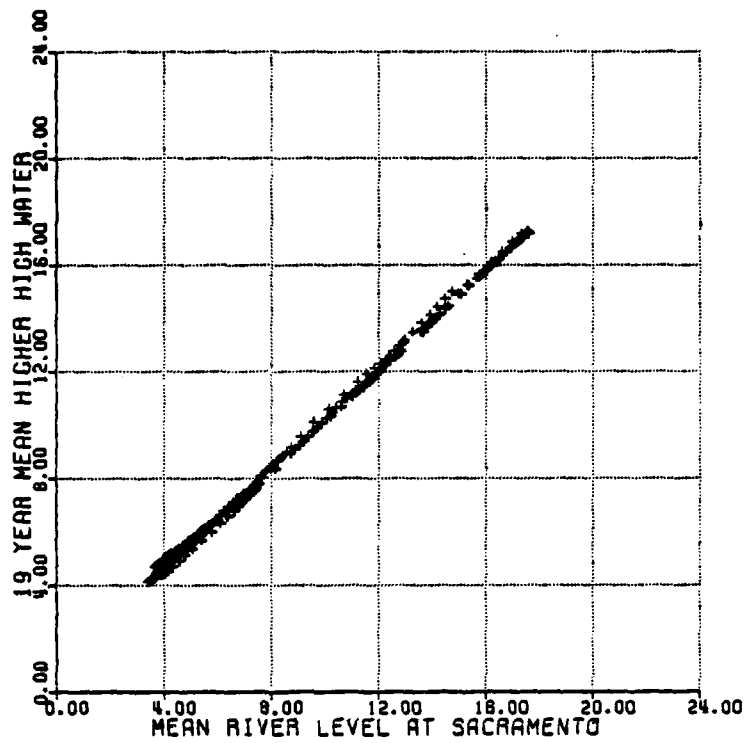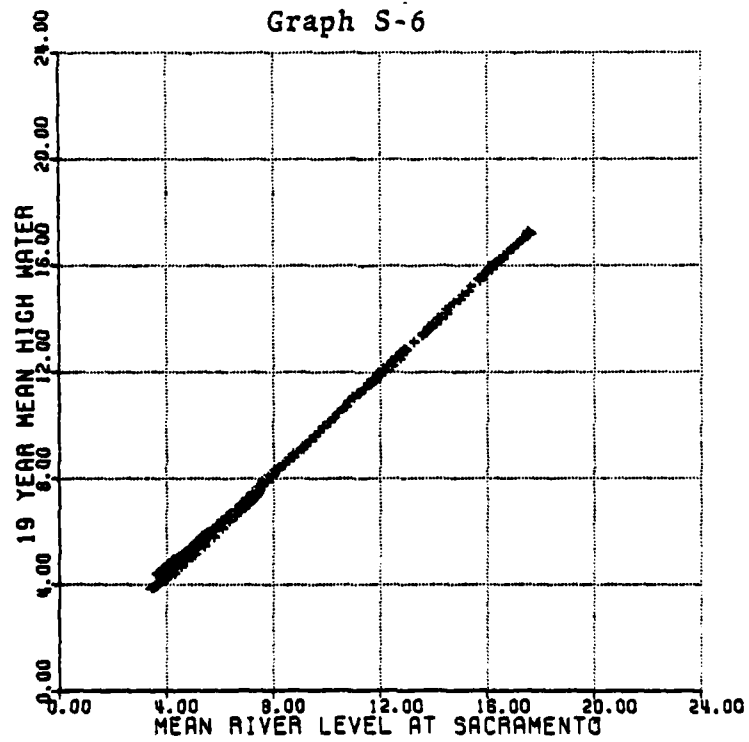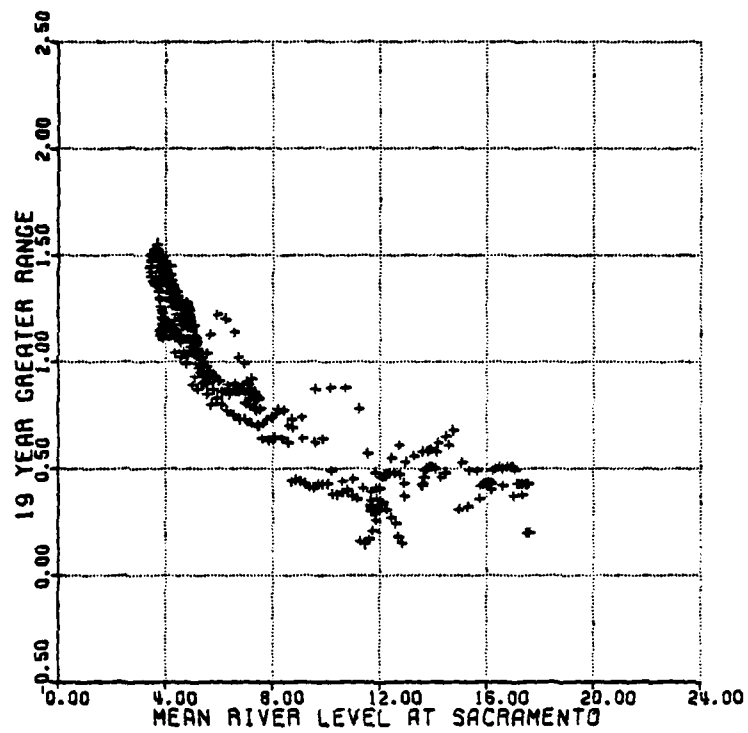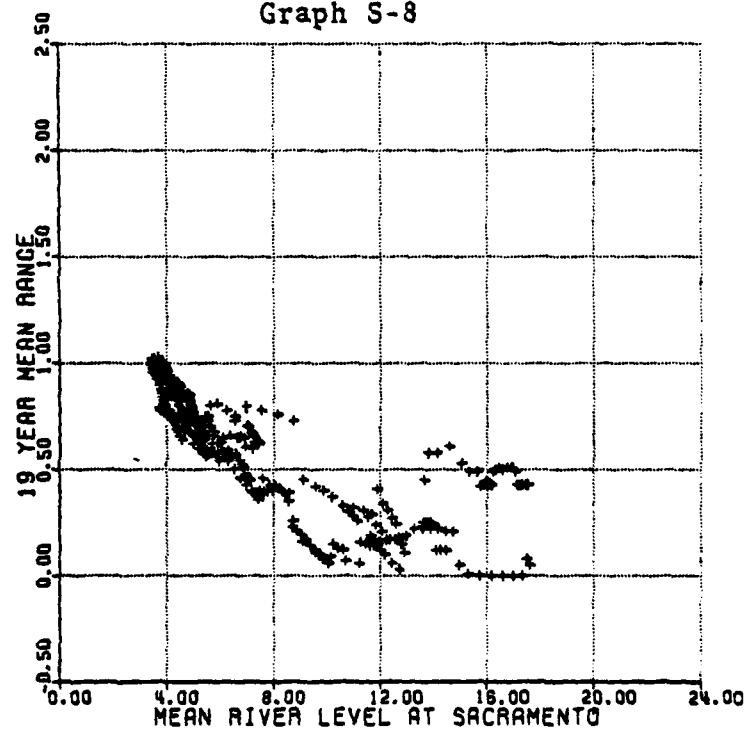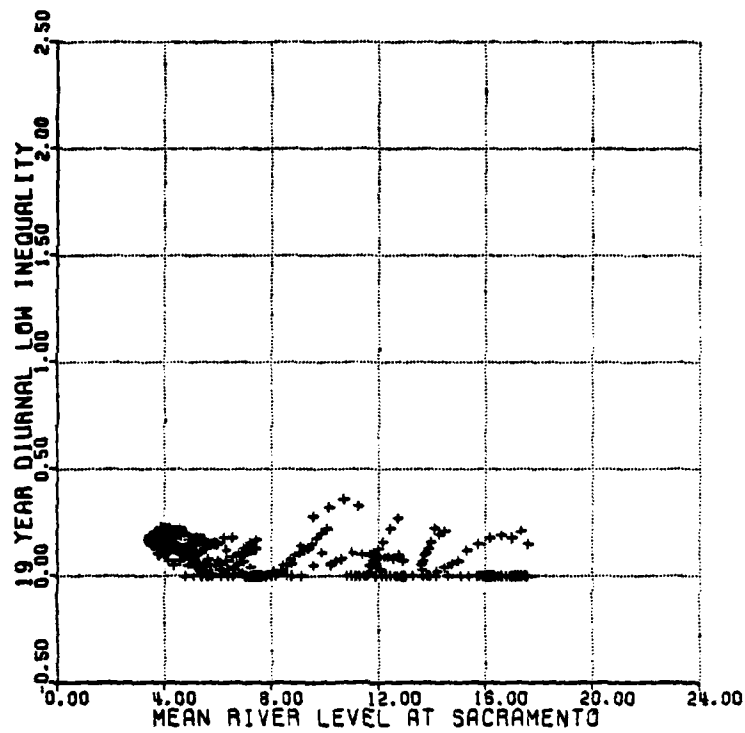
Graph S-10



Graph S-11

167
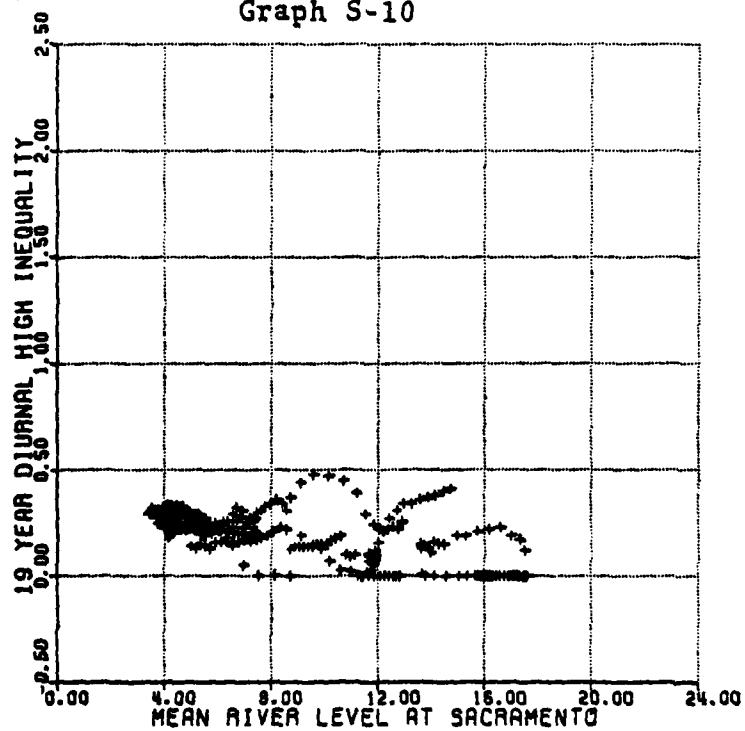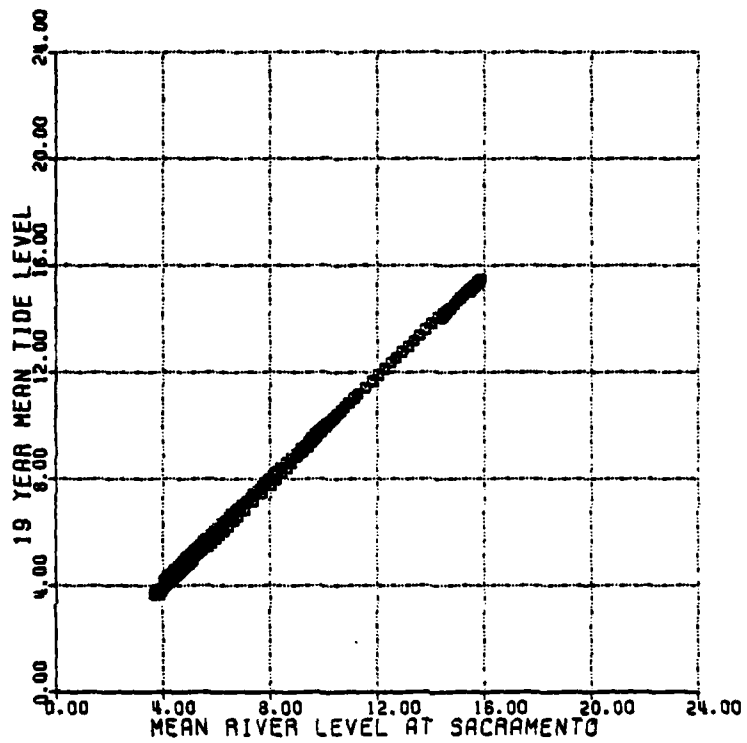
Graph V-3.  FROM 56-DAY COMPARISONS
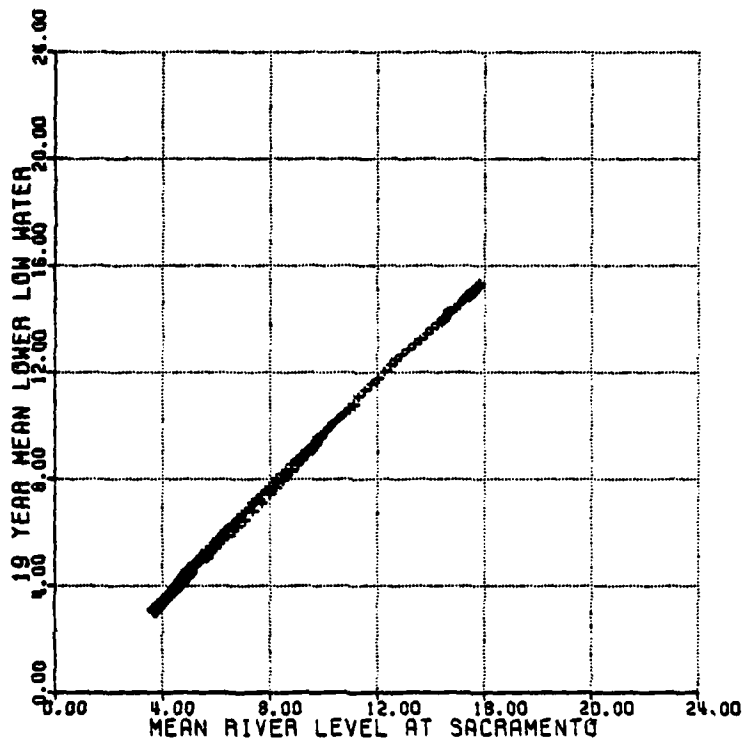
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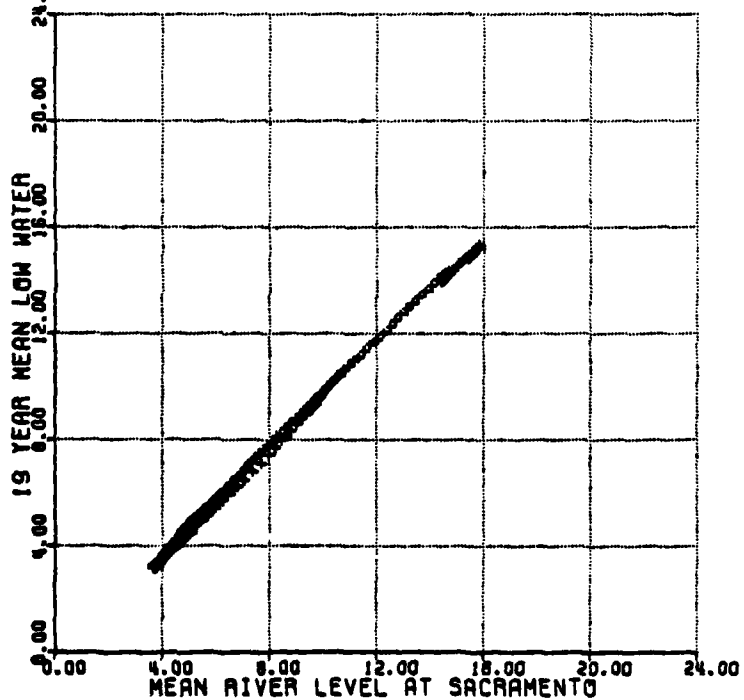


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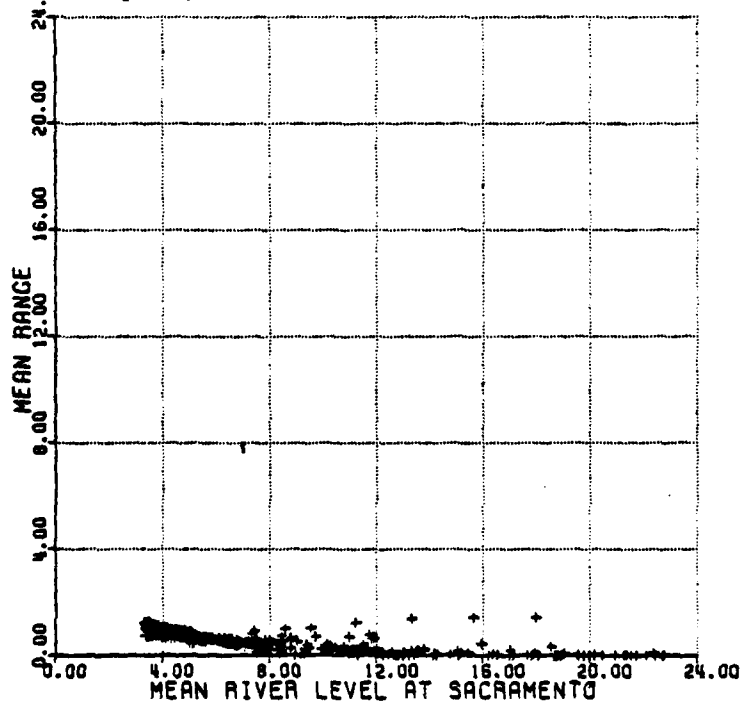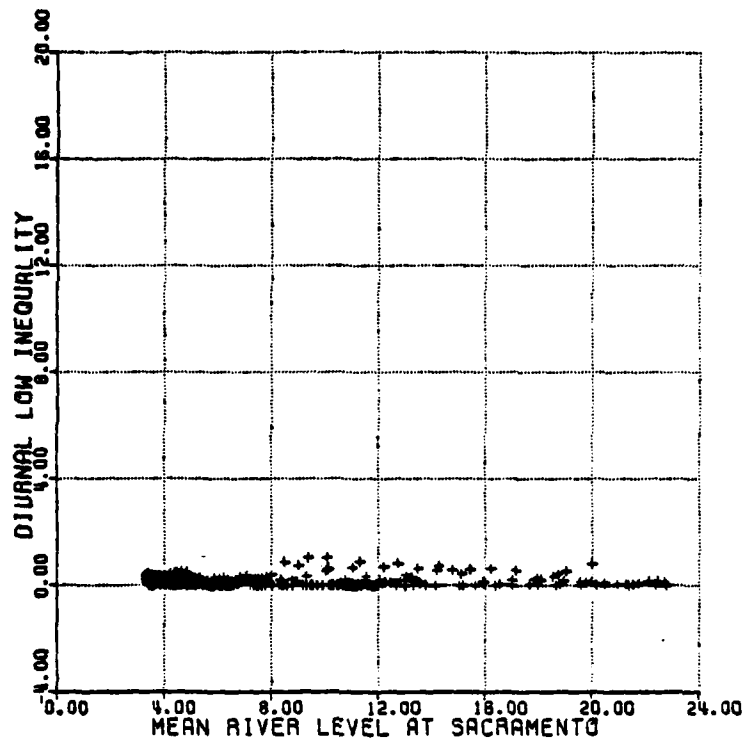
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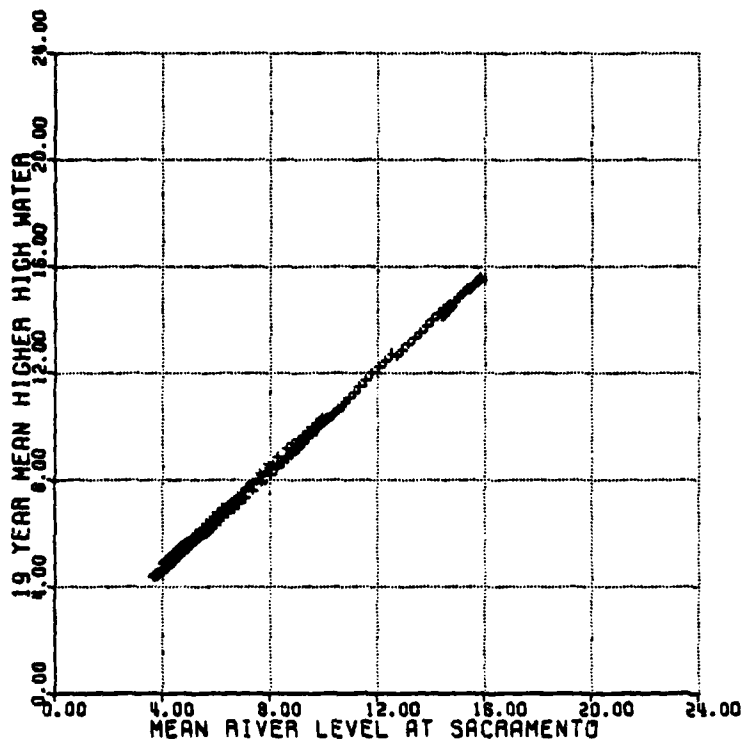
Graph V-6.  FROM 56-DAY COMPARISONS
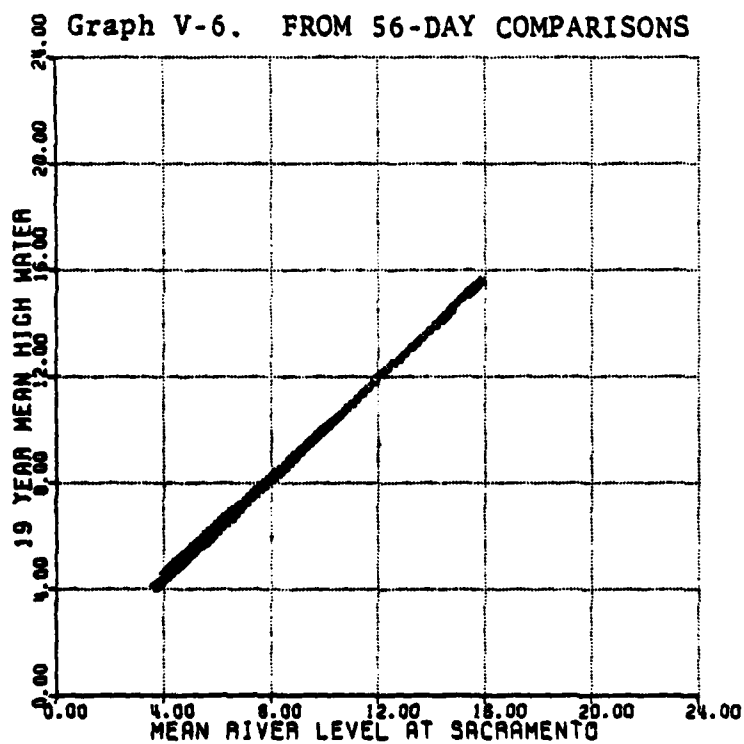


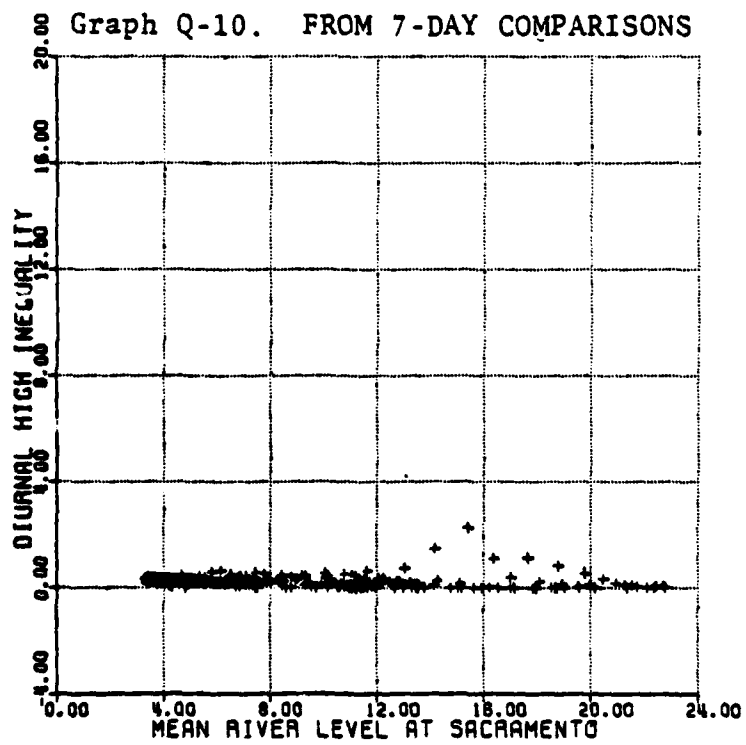Graph V-7.  FROM 56-DAY COMPARISONS

170
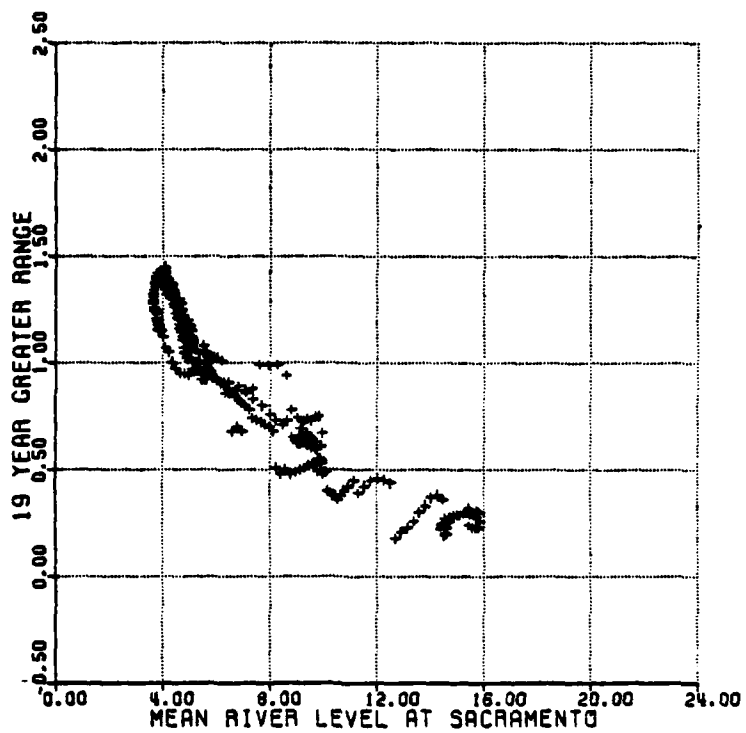
Graph V-8.   FROM 56-DAY COMPARISONS
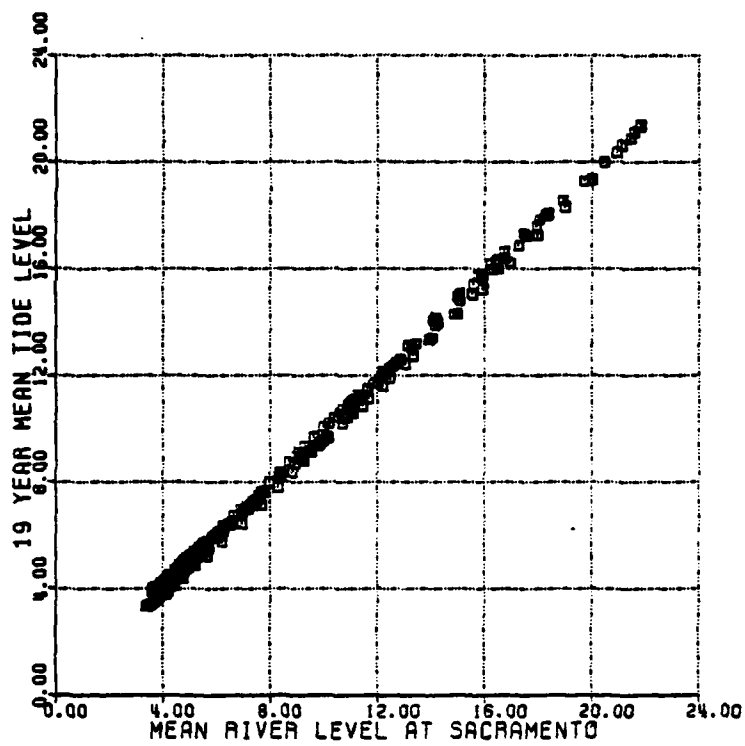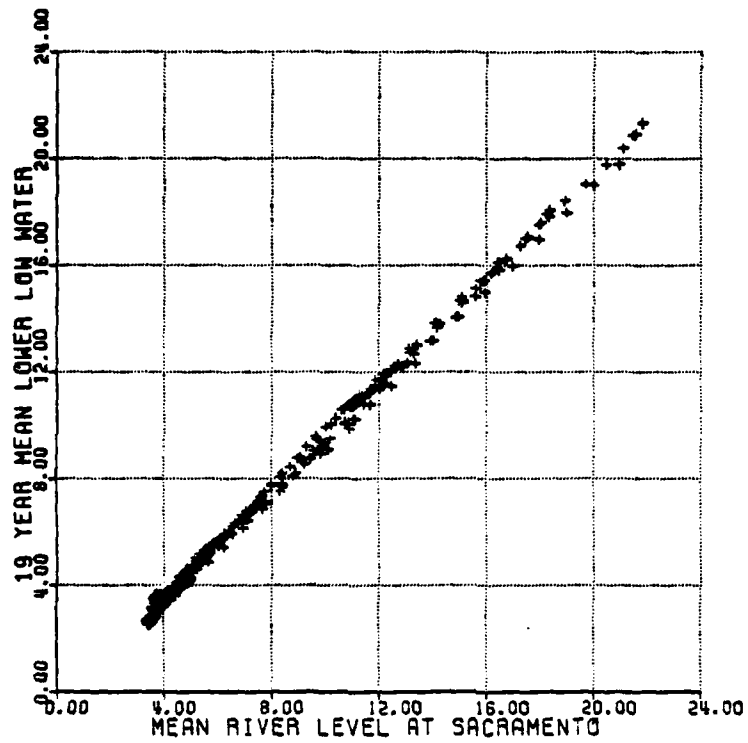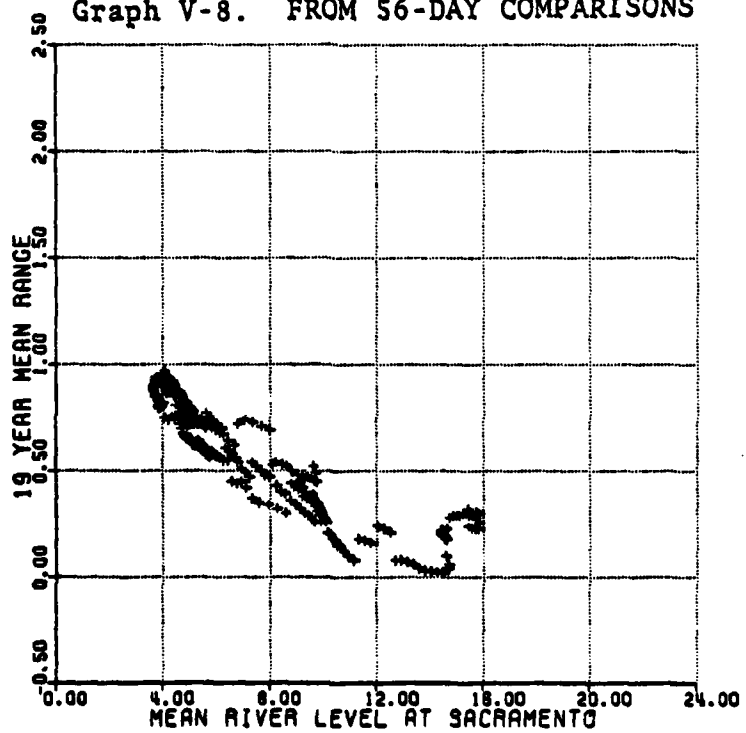


Graph V-9.   FROM 56-DAY COMPARISONS

171

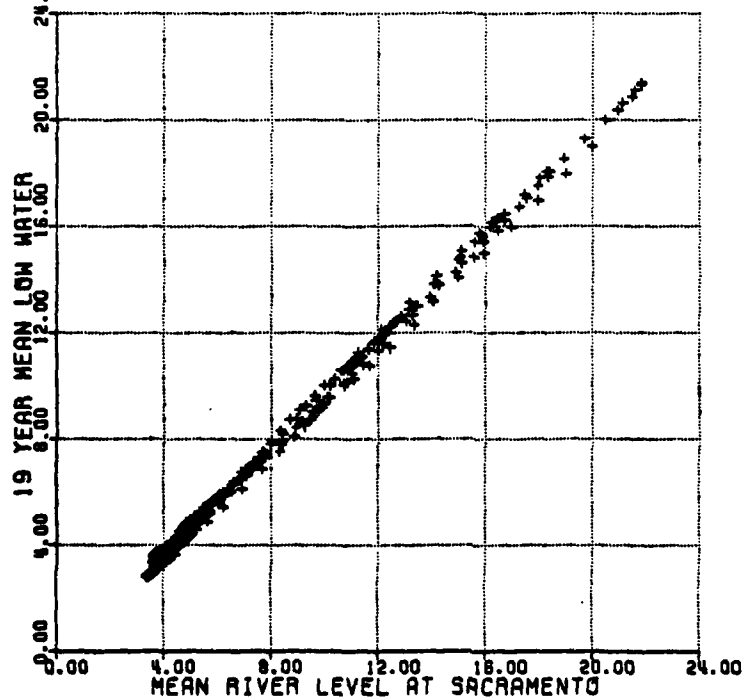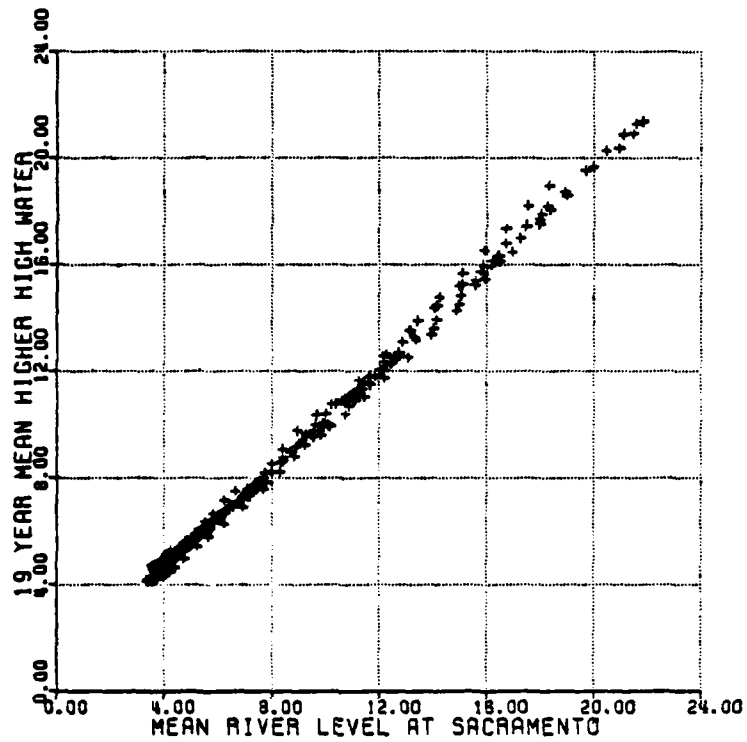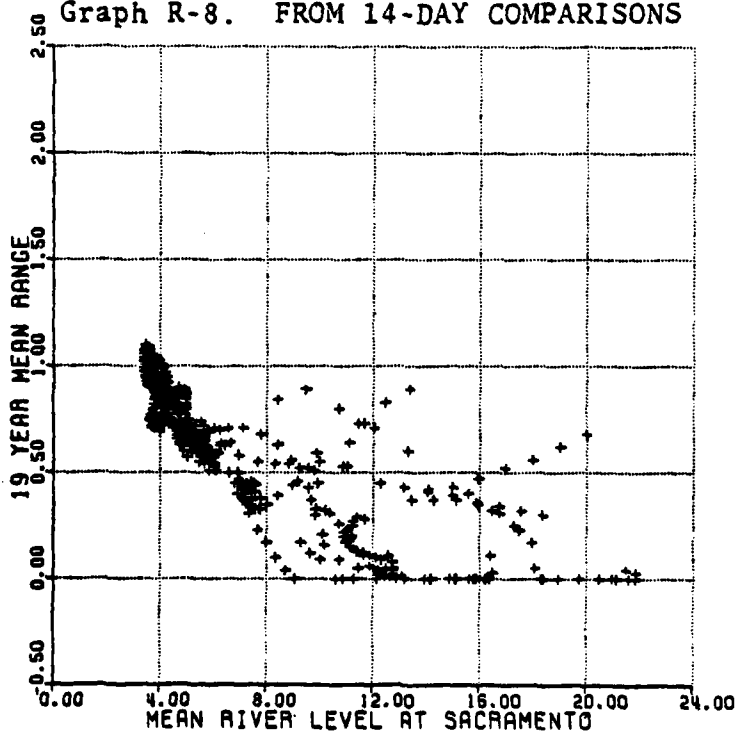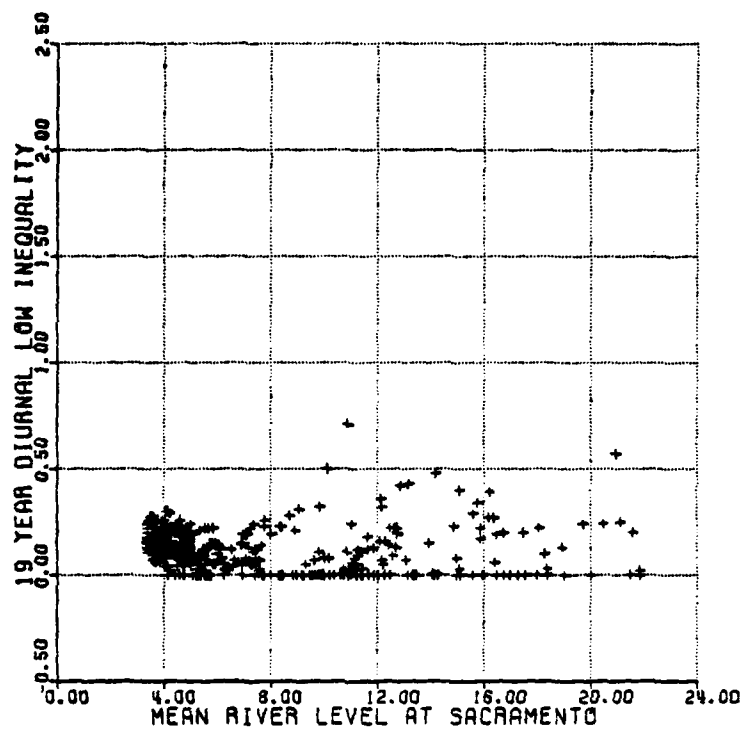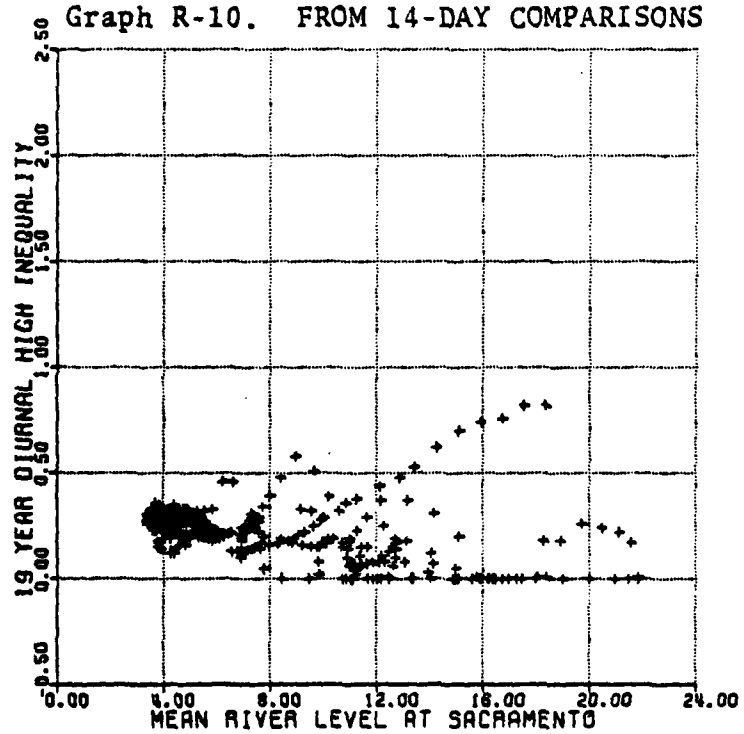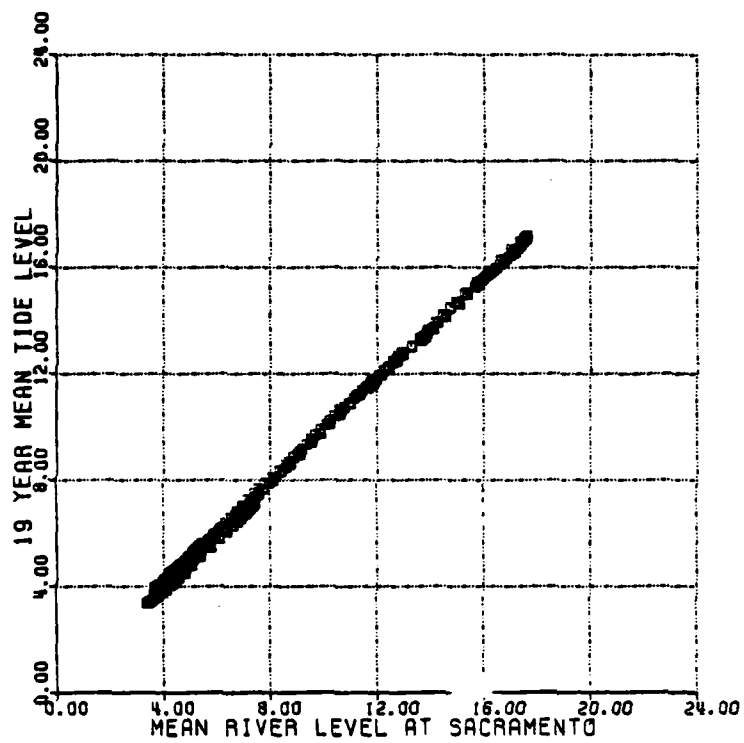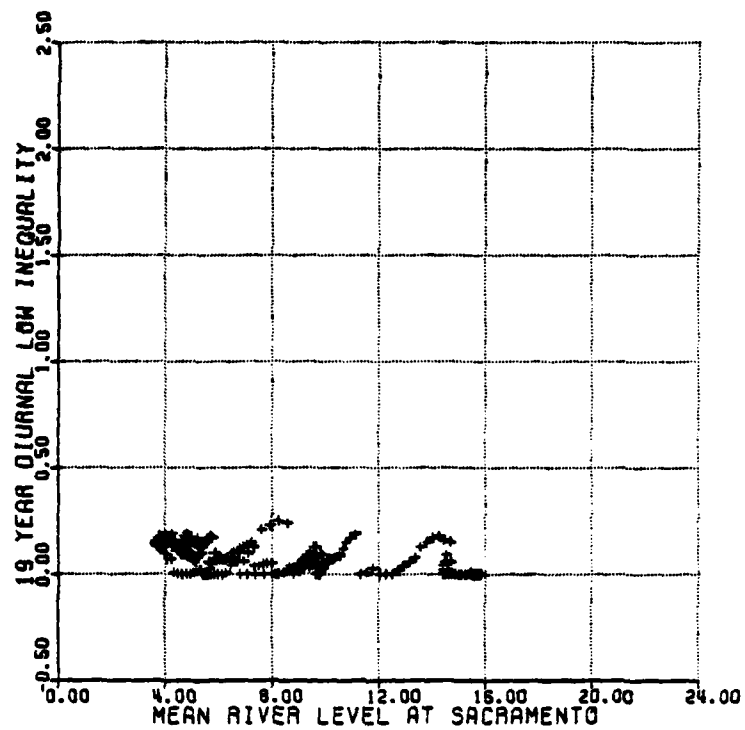Graph V-10.   FROM 56-DAY COMPARISONS
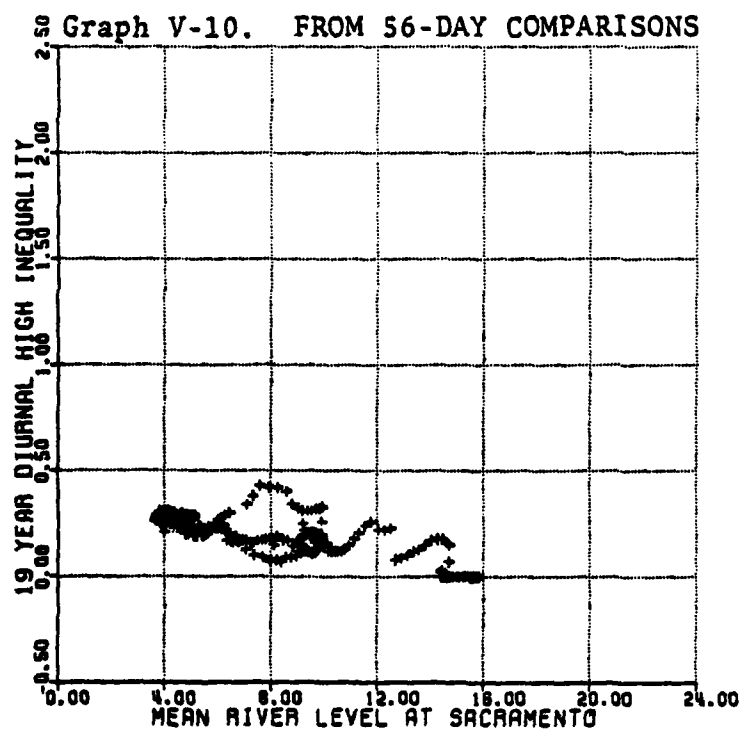


Graph V-11.   FROM 56-DAY COMPARISONS

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# APPENDIX B

```
SUBRCLTINE TC CCMPLTE 19 YEAR TICAL CATUMS FRCM A
COMPARISON OF SIMLLTANEOLS TIDES AT A SUBORDINATE
STATICN FRCM FFESICIC EPCCH 1960-1978

HT1.HT2.TM1.TM2 ARE SYNCRCNIZEC ARRAYS CF HEIGHTS
ANC TIMES CF FIGF ANC LOW WATERS FOR PRESIDIO ANC
THE SECCNDARY STATICN RESPECTIVELY

ITYFE IS AN ARRAY CF THE TYFE CF EACH TIDE
(1=HHh,2=LHh,3=HLh,4=LHW)

D = CIFFERENCE CF CIURNAL
H = FIGH CR HIGHER
L = LCW CF LCWER
M = MEAN
P = PRIMARY CR FRESICIC
C = INECUALITY
S = SECCNCARY CF SLECRCINATE
T = TCTAL
h = WATER

      SLBRCLTINE CCMPAR(HT1,TM1,HT2,TM2,ITYPE,SNGVC,NCOMP,LX
     1.             MHHh,MHW,MTL,MLW,MLLW,CMN,CCHC,CDLC,
     2.             LCWFHS,HIFHS,PMTL,SMTL)
      CIMENSION HT1(232),HT2(232),TM1(232),TM2(232),ITYPE(23
      FEAL*4 MHHh,MHW,MTL,MLW,MLLW,LOWPHS
```

INITIALIZE VARIABLES

```
      IPHHh=0.
      IPLHh=C.
      IPHLh=C.
      IPLLh=C.
      ISHHh=0.
      ISLHh=C.
      ISHLh=C.
      ISLLh=0.
      LOWPHS=0.
      HIFHS=C.
      A=0.
      E=C.
      C=C.
      C=C.
```

SORT EY TYFE CF TICE

```
      CO 3CC I=LX,NCCMP
      KTYPE=ITYFE(I)
      GO TC (31C,32C,330,340),KTYPE
```

SUM THE FIGHER FIGH WATERS

```
310   IPHHh=IPHHh+HT1(I)
      ISHHh=ISHHh+HT2(I)
      HIPHS=HIFHS+(TM2(I)-TM1(I))
      A=A+1.
      GC TC 2SS
```

SUM THE LCWER FIGH WATERS

```
320   IPLHh=IPLHh+HT1(I)
      ISLHh=ISLHh+HT2(I)
      HIFHS=HIFHS+(TM2(I)-TM1(I))
      E=E+1.
      GC TC 2SS
```

```
      SUM THE HIGHER LOW WATERS

330   TPHLW=TPHLW+HT1(I)
      TSHLW=TSHLW+HT2(I)
      LOWPHS=LOWPHS+(TM2(I)-TM1(I))
      C=C+1.
      GO TO 299

      SUM THE LOWER LOW WATERS

340   TPLLW=TPLLW+HT1(I)
      TSLLW=TSLLW+HT2(I)
      LOWPHS=LOWPHS+(TM2(I)-TM1(I))
      C=C+1.
299   CONTINUE
300   CONTINUE

      COMPUTE THE DIFFERENCE TOTALS

      DHHW=TSHHW-TPHHW
      DLHW=TSLHW-TPLHW
      DHLW=TSHLW-TPHLW
      DLLW=TSLLW-TPLLW

      COMPUTE THE MEAN DIFFERENCES

      DMHHW=DHHW/A
      DMLHW=DLHW/B
      DMHLW=DHLW/C
      DMLLW=DLLW/D
      DMHW=.5*(DMHHW+DMLHW)
      DMLW=.5*(DMHLW+DMLLW)
      DMTL=.5*(DMHW+DMLW)

      COMPUTE THE MEAN HIGH AND LOW TIME LAGS

      LOWPHS=LOWPHS/(C+D)
      HIGHS=HIGHS/(A+B)

      COMPUTE THE MEAN TIDES

      FMTL=(TPHHW+TPLHW+TPHLW+TPLLW)/(A+B+C+D)
      FMTL=FMTL-E.61
      CSHHW=TSHHW/A
      CSLHW=TSLHW/B
      CSHLW=TSHLW/C
      CSLLW=TSLLW/D
      SMHW=.5*(CSHHW+CSLHW)
      SMLW=.5*(CSHLW+CSLLW)
      SMTL=.5*(SMHW+SMLW)

      COMPUTE THE MEAN RANGE AND INEQUALITIES

      SMN=SMHW-SMLW
      SDHQ=CSHHW-CSLHW
      SCLQ=CSHLW-CSLLW
      DMN=DMHW-DMLW
      DHQD=DMHHW-DMLHW
      DLQD=DMHLW-DMLLW

      COMPUTE THE RANGE RATIOS

      FMN=SMN/(SMN-DMN)
      RDHQ=SDHQ/(SDHQ-DHQD)
      RCLQ=SCLQ/(SCLQ-DLQD)
```

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```
COMPUTE 19 YEAR MEAN TIDE LEVELS
FROM PRESIDIO EPOCH 1960-1978

      MTL=8.95+(MTL-SNGVD
      CMN=4.10*FMN
      CDHQ=0.6C*RDHQ
      CDLQ=1.55*FDLQ
      MLW=MTL-(.5*CMN)
      MLLW=MLW-CDLQ
      MHW=MTL+(.5*CMN)
      MHHW=MHW+CDHQ
      RETURN




SUBROUTINE TO COMPUTE A RUNNING MEAN FROM AN ARRAY OF DATA

NIN IS THE NUMBER OF MEMBERS IN THE INPUT ARRAY
LTH IS THE NUMBER OF ARRAY MEMBERS IN EACH MEAN VALUE
IDEC IS THE INCREMENT OF MEAN COMPUTATION
  ( IDEC=3, EVERY THIRD MEAN IS COMPUTED)
NOUT IS THE NUMBER OF MEMBERS IN THE OUTPUT ARRAY

      SUBROUTINE ROXCAR(SL,NIN,LTH,IDEC,NOUT)
      REAL*4 SL(6200)
      NOUT=0
      ISTART=1
  20  IEND=ISTART+LTH-1
      IF(IEND.GT.NIN)RETURN
      SUM=0.
      DO 30 I=ISTART,IEND
  30  SUM=SUM+SL(I)
      NOUT=NOUT+1
      SL(NOUT)=SUM/FLOAT(LTH)
      ISTART=ISTART+IDEC
      GO TO 20
      RETURN
```

THIS SUBROUTINE COMPUTES THE HEIGHTS AND TIMES OF HIGH AND
LOW WATERS FROM AN ARRAY GTIDE OF HOURLY HEIGHTS

LE IS THE NUMBER OF MEMBERS IN GTIDE
HEIGHT IS AN ARRAY OF HEIGHTS
TIME IS AN ARRAY OF TIMES IN HOURS AND HUNDREDTHS
CTIME IS AN ARRAY OF TIMES OF DAY IN HOURS AND MINUTES

```
      SUBROUTINE HWLW (GTIDE,LE,HEIGHT,TIME,CTIME)
      DIMENSION GTIDE(12500),HEIGHT(2400),
     1          TIME(2400),CTIME(2400)
      KOLD=0
      J=0
      ID=1
```

INITIAL GUESS OF HIGH OR LOW WATER

```
      DO 60 K=1,LE
      B=GTIDE(K)+GTIDE(K+1)-GTIDE(K+3)-GTIDE(K+4)
      IF(B)1,2,3
    1 IC=-1
      GO TO 4
    3 IC=1
    4 CONTINUE
      IF(ID+IC)60,5,60
    2 IC=-IC
    5 ID=IC
```

FIT A SECOND ORDER CURVE TO THE HOURLY HEIGHTS

```
      J=J+1
      FZ=GTIDE(K)+4.*GTIDE(K+1)+9.*GTIDE(K+2)+16.*GTIDE(K+3)
     1+25.*GTIDE(K+4)
      FC=GTIDE(K)+GTIDE(K+1)+GTIDE(K+2)+GTIDE(K+3)
     1    +GTIDE(K+4)
      FL=GTIDE(K)+2.*GTIDE(K+1)+3.*GTIDE(K+2)+4.*GTIDE(K+3)
     1    +5.*GTIDE(K+4)
```

COMPUTE HEIGHT AND TIME FROM THE EXTREMA OF THE CURVE

```
      A2=-(3./11.)*(((FZ-11.*FC)/6.)-(15.*FZ-55.*FL)/35.)
      A1=(FZ-11.*FC)/60.-((374./60.)*A2)
      A0=FC/5.-3.*A1-11.*A2
      TIME(J)=-A1/(2.*A2)
      HEIGHT(J)=A0+TIME(J)*A1+TIME(J)**2*A2
      TIME(J)=TIME(J)+FLOAT(K)-2.
```

COMPUTE TIME IN HOURS AND MINUTES

```
      TEMPT=TIME(J)*100.
      TEMPT=.004*AMOD(TEMPT,100.)
      CTIME(J)=AMOD(TIME(J),24.)-TEMPT
   59 CONTINUE
   60 CONTINUE
      RETURN
```

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